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Introduction to Quartz Frequency Standards

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October 1992

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13. ABSTRACT *(Maximum 200 words)*
The fundamentals of quartz frequency standards are reviewed. The subjects discussed include: crystal resonators and oscillators, oscillator types, and the characteristics and limitations of temperature-compensated crystal oscillators (TCXO) and oven-controlled crystal oscillators (OCXO). The oscillator instabilities discussed include: aging, noise, frequency vs. temperature, warmup, acceleration effects, magnetic field effects, atmospheric pressure effects, radiation effects, and interactions among the various effects. Guidelines are provided for oscillator comparison and selection. Discussions of specifications are also included, as are references and suggestions for further reading.

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I. Introduction

More than one billion (i.e., 10^9) quartz crystal oscillators are produced annually for applications ranging from inexpensive watches and clocks to radionavigation and spacecraft tracking systems. The fundamentals of quartz oscillators are reviewed in this report, with emphasis on quartz frequency standards (as opposed to inexpensive clock oscillators). The subjects discussed include: crystal resonators and oscillators, oscillator types, and the characteristics and limitations of temperature-compensated crystal oscillators (TCXO) and oven-controlled crystal oscillators (OCXO). The oscillator instabilities discussed include: aging, noise, frequency vs. temperature, warmup, acceleration effects, magnetic field effects, atmospheric pressure effects, radiation effects, and interactions among the various effects. Guidelines are provided for oscillator comparison and selection. Discussions of specifications are also included, as are references and suggestions for further reading.

II. Crystal Oscillators

A. Generalized Crystal Oscillator

1. Oscillator Basics

Figure 1 is a greatly simplified circuit diagram that shows the basic elements of a crystal oscillator [1-3]. The amplifier of a crystal oscillator consists of at least one active device, the necessary biasing networks; and may include other elements for band limiting, impedance matching, and gain control. The feedback network consists of the crystal resonator, and may contain other elements, such as a variable capacitor for tuning.

The frequency of oscillation is determined by the requirement that the closed loop phase shift = $2n\pi$, where n is an integer, usually 0 or 1. When the oscillator is initially energized, the only signal in the circuit is noise. That component of noise, the frequency of which satisfies the phase condition for oscillation, is propagated around the loop with increasing amplitude. The rate of increase depends on the excess loop gain and on the bandwidth of the crystal network. The amplitude continues to increase until the amplifier gain is reduced, either by the nonlinearities of the active elements (in which case it is *self limiting*) or by an external level-control method.

At steady state, the closed-loop gain = 1. If a phase perturbation $\Delta\phi$ occurs, the frequency of oscillation must shift by a Δf in order to maintain the $2n\pi$ phase condition. It can be shown that for a series-resonance oscillator

$$\frac{\Delta f}{f} = -\frac{\Delta\phi}{2Q_L},$$

where Q_L is the loaded Q of the crystal in the network [1]. ("Crystal" and "resonator" are

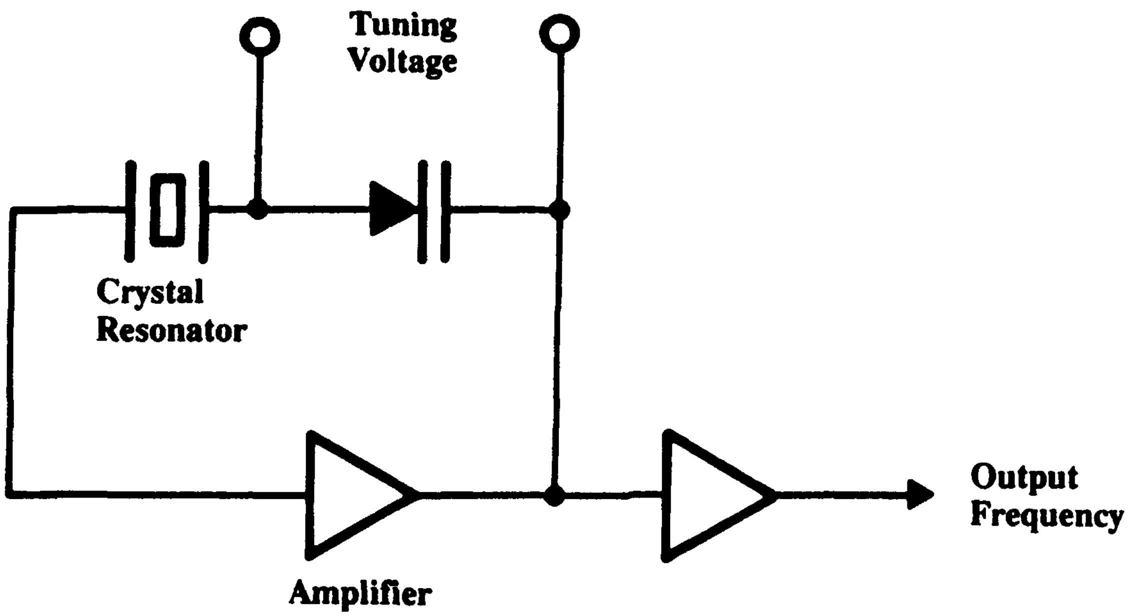


Figure 1. Crystal oscillator - simplified circuit diagram.

often used interchangeably with "crystal unit," although "crystal unit" is the official name. See references 3 to 6 for further information about crystal units.) Crystal oscillator design information can be found in references 1, 2, 5 and 7. The abbreviation for crystal oscillator is XO.

2. Crystal Unit Equivalent Circuit

A quartz crystal unit is a quartz wafer to which electrodes have been applied, and which is hermetically sealed in a holder structure. (The wafer is often referred to as the "blank," or the "crystal plate".) Although the design and fabrication of crystal units comprise a complex subject, the oscillator designer can treat the crystal unit as a circuit component and just deal with the crystal unit's equivalent circuit.

The mechanically vibrating system and the circuit shown in Figure 2 are "equivalent," because each can be described by the same differential equation [6]. The mass, spring, and damping element (i.e., the dashpot) correspond to the inductor, capacitor and resistor. The driving force corresponds to the voltage, the displacement of the mass to the charge on the capacitor, and the velocity to the current.

A crystal resonator is a mechanically vibrating system that is linked, via the piezoelectric effect, to the electrical world. Figure 3 shows a (simplified) equivalent circuit (of one mode of vibration) of a resonator, together with the circuit symbol for a crystal

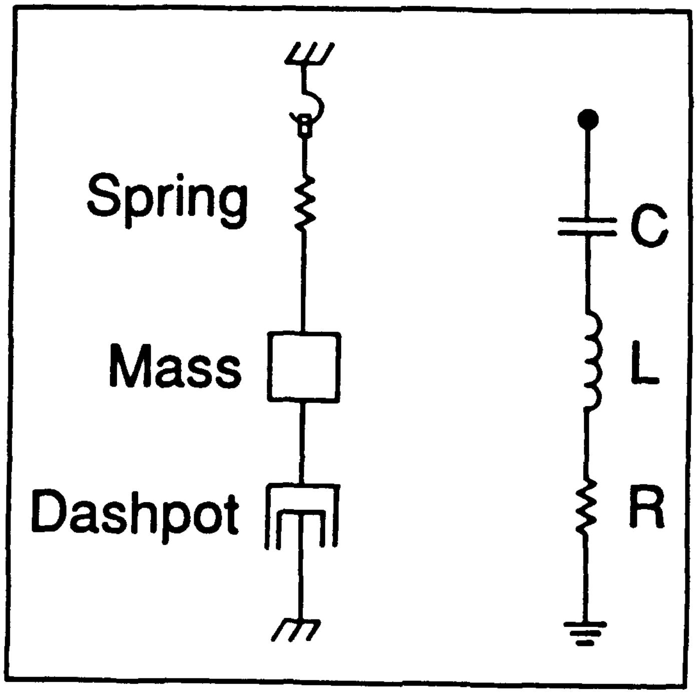


Figure 2. Equivalent circuit of a mechanically vibrating system.

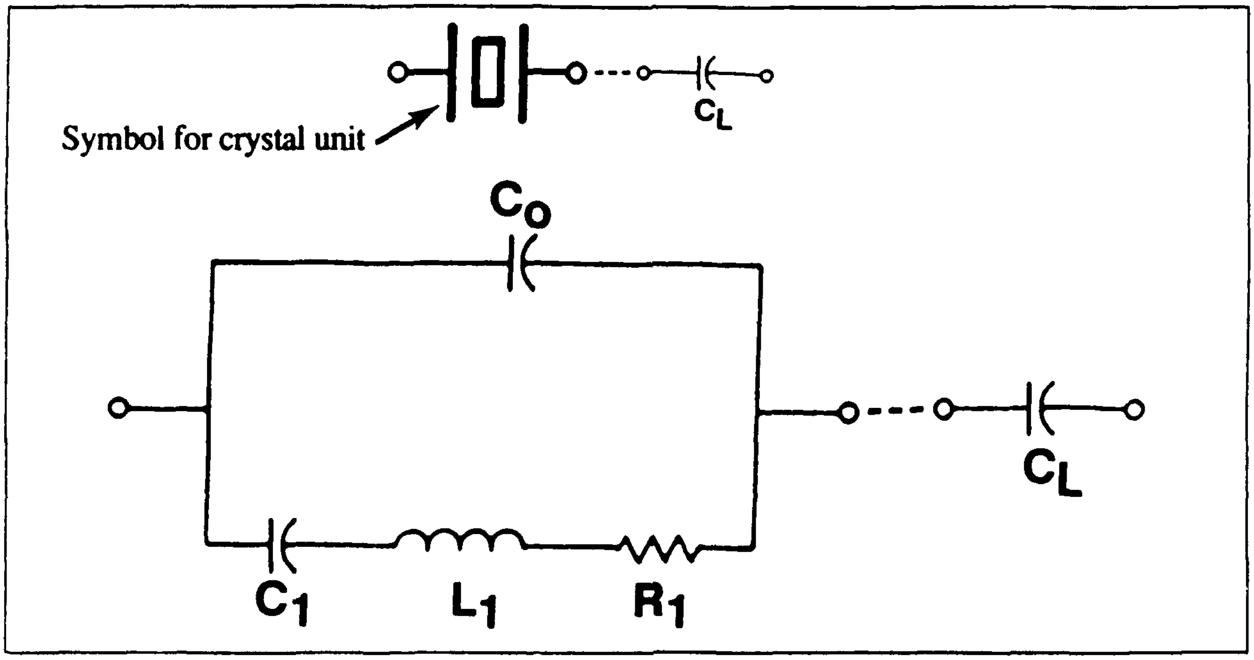


Figure 3. Equivalent circuit of crystal unit with load capacitor.

unit. A load capacitor C_L is shown in series with the crystal. C_0, called the "shunt" capacitance, is the capacitance due to the electrodes on the crystal plate plus the stray capacitances due to the crystal enclosure. The R_1, L_1, C_1 portion of the circuit is the "motional arm" which arises from the mechanical vibrations of the crystal.

The C_0 to C_1 ratio is a measure of the interconversion between electrical and mechanical energy stored in the crystal, i.e., of the piezoelectric coupling factor, k. C_0/C_1 increases with the square of the overtone number; the relationship of C_0/C_1 to k and N is $2C_0/C_1 = [\pi N^2/2k]$, where N is the overtone number. When a dc voltage is applied to the electrodes of a resonator, the capacitance ratio C_0/C_1 is also a measure of the ratio of electrical energy stored in the capacitor formed by the electrodes to the energy stored elastically in the crystal due to the lattice strains produced by the piezoelectric effect. Figure 4 shows the reactance versus frequency characteristic of the crystal unit. The C_0/C_1 is also inversely proportional to the antiresonance-resonance frequency separation (i.e., the pole-zero spacing) which is an especially important parameter in filter applications. The slope of the reactance vs. frequency curve near f_s is inversely proportional to C_1, i.e., $\Delta X/(\Delta f/f) \approx 1/\pi f C_1$ near f_s, where X is the reactance. C_1 is, therefore, a measure of the crystal's "stiffness," i.e., its tunability - see the equation on the next page.

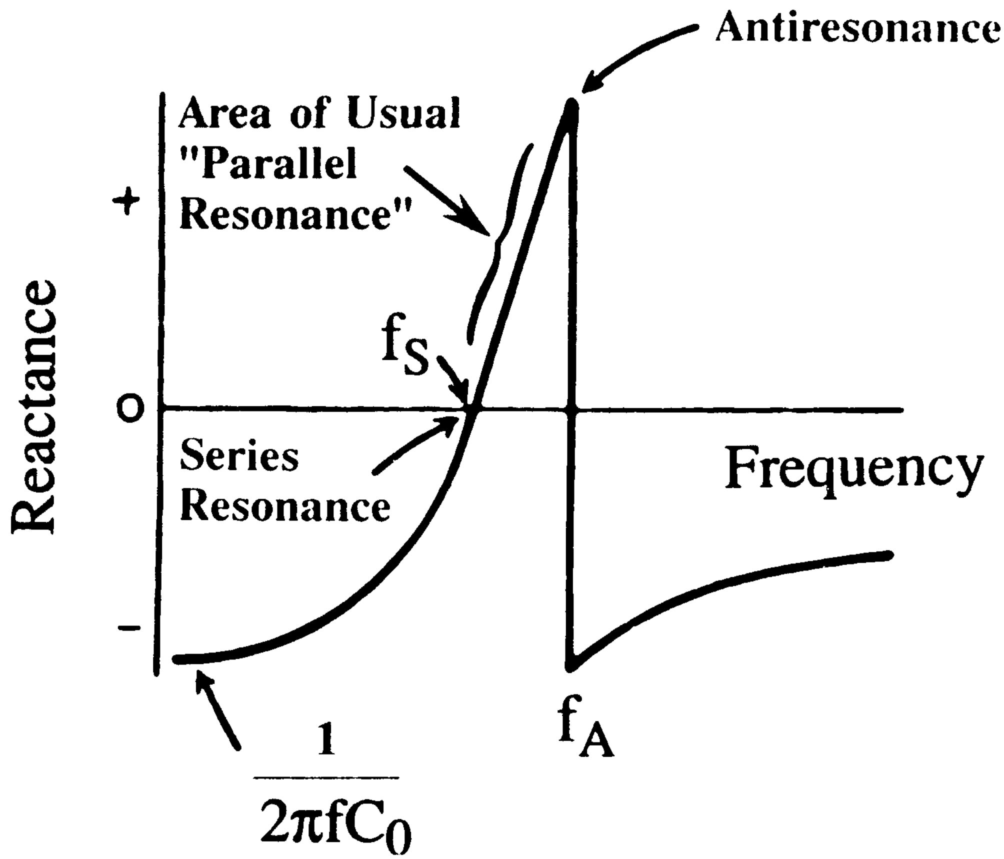


Figure 4. Reactance versus frequency of a crystal unit.

When the load capacitor is connected in series with the crystal, the frequency of operation of the oscillator is increased by a $\Delta f'$, where $\Delta f'$ is given by

$$\frac{\Delta f'}{f} \approx \frac{C_1}{2(C_0+C_L)} .$$

When an inductor is connected in series with the crystal, the frequency of operation is decreased. The ability to change the frequency of operation by adding or changing a reactance allows for compensation of the frequency versus temperature variations of crystal units in TCXOs, and for tuning the output frequency of voltage controlled crystal oscillators (VCXO); in both, the frequency is changed by changing the voltage on a varactor.

For the simple RLC circuit of Figure 2, the width of the resonance curve is inversely proportional to the quality factor Q, but in a crystal oscillator, the situation is complicated by the presence of C_0 and by the fact that the operating Q is lower than the resonator Q. For a quartz resonator, $Q = (2\pi f_s C_1 R_1)^{-1}$. References 3, 5 and 6 contain further details on the equivalent circuit.

Some of the numerous advantages of a quartz crystal resonator over a tank circuit built from discrete R's, C's and L's are that the crystal is far stiffer and has a far higher Q than what could be built from normal discrete components. For example, a 5 MHz fundamental mode AT-cut crystal may have C_1 = 0.01 pF, L_1 = 0.1 H, R_1 = 5 Ω, and Q = 10^6. A 0.01 pF capacitor is not available, since the leads attached to such a capacitor would alone probably contribute more than 0.01 pF. Similarly a 0.1 H inductor would be physically large, it would need to include a large number of turns, and would need to be superconducting in order to have a $\leq 5\Omega$ resistance.

3. Stability versus Tunability

In most crystal oscillator types, a variable-load capacitor is used to adjust the frequency of oscillation to the desired value. Such oscillators operate at the parallel resonance region of Figure 4, where the reactance versus frequency slope (i.e., the "stiffness") is inversely proportional to C_1. For maximum frequency stability with respect to reactance (or phase) perturbations in the oscillator circuit, the reactance slope (or phase slope) must be maximum. This requires that the C_1 be minimum. The smaller the C_1, however, the more difficult it is to tune the oscillator (i.e., the smaller is $\Delta f'$ for a given change in C_L). The highest stability oscillators use crystal units that have a small C_1 (and a high Q). Since C_1 decreases rapidly with overtone number, high-stability oscillators generally use third- or fifth-overtone crystal units. Overtones higher than fifth are rarely used, because R_1 also increases rapidly with overtone number, and some tunability is usually desirable in order to allow setting the oscillator to the desired frequency.

Wide-tuning-range VCXOs use fundamental mode crystal units of large C_1. Voltage control is used for the following purposes: to frequency or phase lock two oscillators; for frequency modulation; for compensation, as in a TCXO (see below); and for calibration (i.e., for adjusting the frequency to compensate for aging). Whereas a high-stability, ovenized 10-MHz VCXO may have a frequency adjustment range of $\pm 5 \times 10^{-7}$ and an aging rate of 2×10^{-8} per year, a wide-tuning-range 10-MHz VCXO may have a tuning range of ±50 parts per million (ppm) and an aging rate of 2 ppm per year.

In general, making an oscillator tunable over a wide frequency range degrades its stability because making an oscillator susceptible to intentional tuning also makes it susceptible to factors that result in unintentional tuning. For example, if an oven-controlled crystal oscillator (OCXO) is designed to have a stability of 1×10^{-12} for a particular averaging time and a tunability of 1×10^{-7}, then the crystal's load reactance must be stable to 1×10^{-5} for that averaging time. Achieving such load-reactance stability is difficult because the load-reactance is affected by stray capacitances and inductances, by the stability of the varactor's capacitance versus voltage characteristic, and by the stability of the voltage on the varactor. Moreover, the 1×10^{-5} load-reactance stability must be maintained not only under benign conditions, but also under changing environmental conditions (temperature, vibration, radiation, etc.). Therefore, the wider the tuning range of an oscillator, the more difficult it is to maintain a high stability.

4. Quartz and the Quartz Crystal Unit

A quartz crystal unit's high Q and high stiffness (small C_1) make it the primary frequency and frequency-stability determining element in a crystal oscillator. The Q values of crystal units are much higher than those attainable with other circuit elements. In general-purpose crystal units, Qs are generally in the range of 10^4 to 10^6. A high-stability 5-MHz crystal unit's Q is typically in the range of two to three million. The intrinsic Q, limited by internal losses in the crystal, has been determined experimentally to be inversely proportional to frequency (i.e., the Qf product is a constant for a given resonator type). For AT- and SC-cut resonators, the maximum Qf = 16 million when f is in MHz.

Quartz (which is a single-crystal form of SiO_2) has been the material of choice for stable resonators since shortly after piezoelectric crystals were first used in oscillators - in 1918. Although many other materials have been explored, none has been found to be better than quartz. Quartz is the only material known that possesses the following combination of properties:

1. It is piezoelectric ("pressure electric"; *piezein* means "to press" in Greek).
2. Zero temperature coefficient resonators can be made when the plates are cut along the proper directions with respect to the crystallographic axes of quartz.

3. Of the zero temperature coefficient cuts, one, the SC-cut (see below), is "stress compensated."
4. It has low intrinsic losses (i.e., quartz resonators can have high Q's).
5. It is easy to process because it is hard but not brittle, and, under normal conditions, it has low solubility in everything except the fluoride etchants.
6. It is abundant in nature.
7. It is easy to grow in large quantities, at low cost, and with relatively high purity and perfection.

Of the man-grown single crystals, quartz, at more than 2000 tons per year (in 1991), is second only to silicon in quantity grown.

The direct piezoelectric effect was discovered by the Curie brothers in 1880. They showed that when a weight was placed on a quartz crystal, charges appeared on the crystal surface; the magnitude of the charge was proportional to the weight. In 1881, the converse piezoelectric effect was illustrated; when a voltage was applied to the crystal, the crystal deformed due to the lattice strains caused by the effect. The strains reversed when the voltage was reversed.

Of the 32 crystal classes, 20 exhibit the piezoelectric effect (but only a few of these are useful). Piezoelectric crystals lack a center of symmetry. When a force deforms the lattice, the centers of gravity of the positive and negative charges in the crystal can be separated so as to produce surface charges. The piezoelectric effect can provide a coupling between an electrical circuit and the mechanical properties of a crystal. Under the proper conditions, a "good" piezoelectric resonator can stabilize the frequency of an oscillator circuit.

Quartz crystals are highly *anisotropic*, that is, the properties vary greatly with crystallographic direction. For example, when a quartz sphere is etched in hydrofluoric acid, the etching rate is more than 100 times faster along the fastest etching rate direction, the Z-direction, than along the slowest direction, the slow-X-direction. The constants of quartz, such as the thermal expansion coefficient and the temperature coefficients of the elastic constants, also vary with direction. That crystal units can have zero temperature coefficients of frequency is a consequence of the temperature coefficients of the elastic constants ranging from negative to positive values.

The locus of zero-temperature-coefficient cuts in quartz is shown in Figure 5. The X, Y, and Z directions have been chosen to make the description of properties as simple as possible. The Z-axis in Figure 5 is an axis of threefold symmetry in quartz; in other words, the physical properties repeat every 120° as the crystal is rotated about the Z-axis. The cuts usually have two-letter names, where the "T" in the name indicates a temperature-compensated cut; for instance, the AT-cut was the first temperature-compensated cut discovered. The FC, IT, BT, and RT-cuts are other cuts along the zero-

temperature coefficient locus. These cuts were studied in the past (before the discovery of the SC-cut) for some special properties, but are rarely used today. The highest-stability crystal oscillators employ SC-cut or AT-cut crystal units.

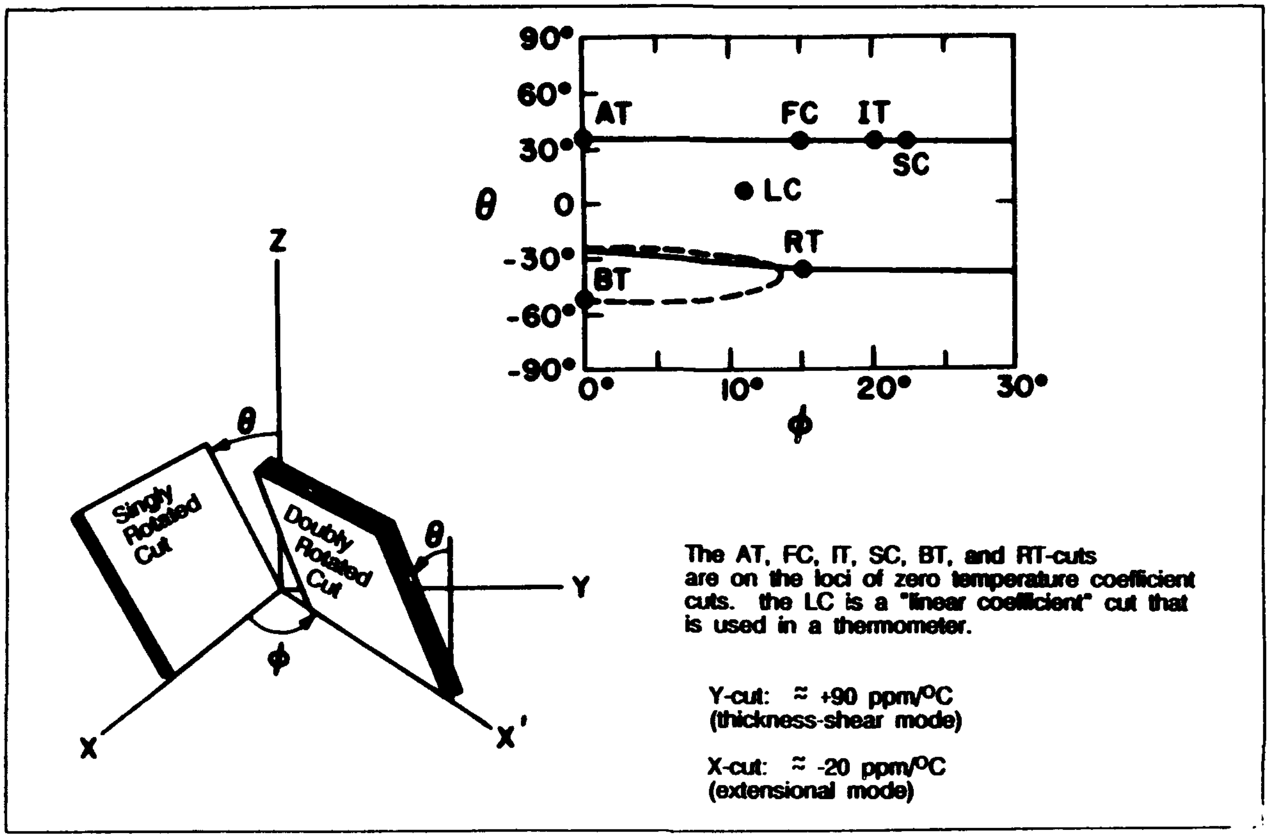


Figure 5. Zero-temperature-coefficient cuts of quartz.

Because the properties of a quartz crystal unit depend strongly on the angles of cut of the crystal plate, in the manufacture of crystal units, the plates are cut from a quartz bar along precisely controlled directions with respect to the crystallographic axes. The orientations of the plates are checked by means of X-ray diffraction. In some applications, the orientations must be controlled with accuracies of a few seconds of angle. After shaping to required dimensions, metal electrodes are applied to the wafer. Circular plates with circular electrodes are the most commonly used geometries, although the blanks and electrodes may also be of other geometries. The electroded wafer is mounted in a holder structure [8]. Figure 6 shows the two common types of holder structures used for resonators with frequencies greater than 1 MHz. (The 32-kHz tuning fork resonators used in quartz watches are packaged typically in small tubular enclosures.)

Because quartz is piezoelectric, a voltage applied to the electrodes causes the quartz plate to deform slightly. The amount of deformation due to an alternating voltage

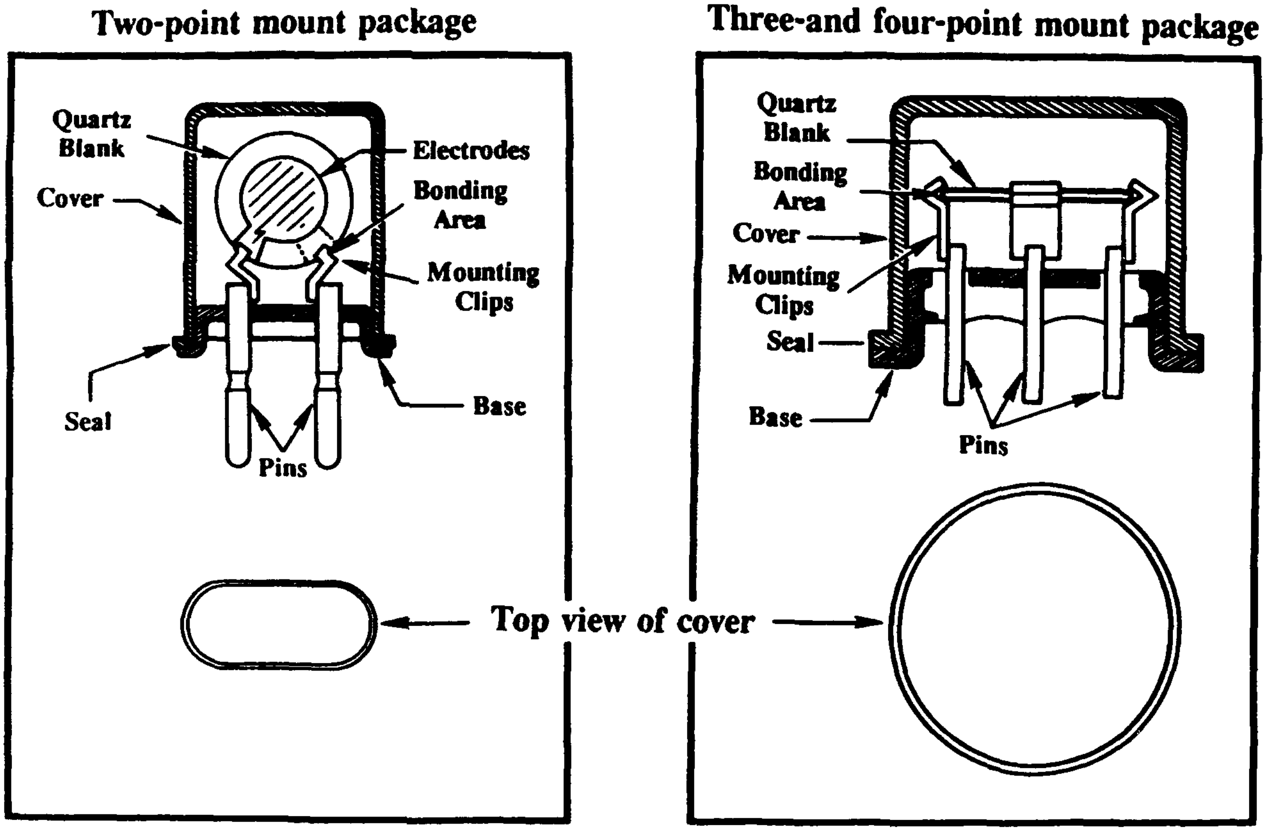


Figure 6. Typical constructions of AT-cut and SC-cut crystal units: (a) two-point mount package; (b) three- and four-point mount package.

depends on how close the frequency of the applied voltage is to a natural mechanical resonance of the crystal. To describe the behavior of a resonator, the differential equations for Newton's laws of motion for a continuum, and for Maxwell's equations, must be solved with the proper electrical and mechanical boundary conditions at the plate surfaces [9]. Because quartz is anisotropic and piezoelectric, with 10 independent linear constants and numerous higher order constants, the equations are complex, and have never been solved in closed form for physically realizable three-dimensional resonators. Nearly all theoretical works have used approximations. The nonlinear elastic constants, although small, are the source of some of the important instabilities of crystal oscillators; such as the acceleration sensitivity, the thermal-transient effect, and the amplitude-frequency effect, each of which is discussed in this report.

In an ideal resonator, the amplitude of vibration is maximum at the center of the electrodes; it falls off exponentially outside the electrodes, as shown in the lower right portion of Figure 7. In a properly designed resonator, a negligible amount of energy is

lost to the mounting and bonding structure, i.e., the edges must be inactive in order for the resonator to be able to possess a high Q. The displacement of a point on the resonator surface is proportional to the drive current. At the typical drive currents used in (e.g., 10 MHz) thickness shear resonators, the peak displacement is on the order of a few atomic spacings. (The peak acceleration of a point on the electrodes is on the order of 1 million g.)

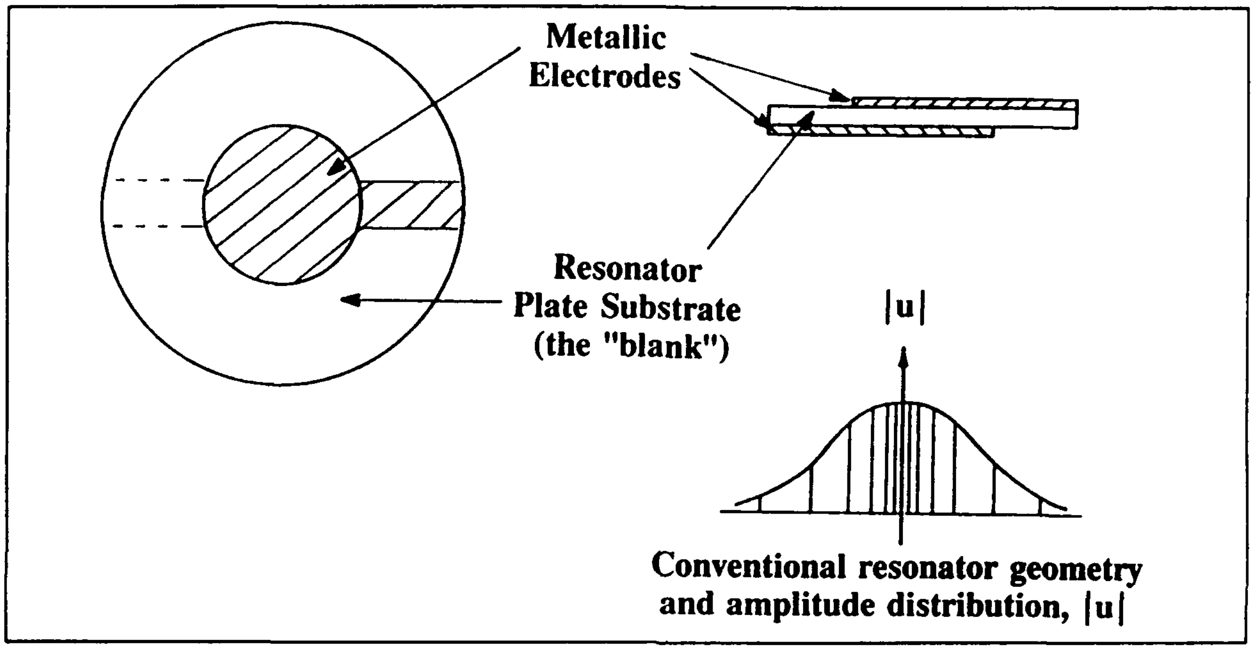


Figure 7. Resonator vibration amplitude distribution for a circular plate with circular electrodes.

As the drive level (the current through a crystal) increases, the crystal's amplitude of vibration also increases, and the effects due to the nonlinearities of quartz become more pronounced. Among the many properties that depend on the drive level are: resonance frequency, motional resistance R_1, phase-noise, and frequency vs. temperature anomalies (called *activity dips*), which are discussed in another section of this report. The drive-level dependence of the resonance frequency, called the *amplitude-frequency effect,* is illustrated in Figure 8 [10]. The frequency change with drive level is proportional to the square of the drive current; the coefficient depends on resonator design [11]. Because of the drive-level dependence of frequency, the highest stability oscillators usually contain some form of automatic level control in order to minimize frequency changes due to oscillator circuitry changes. At high drive levels, the nonlinear effects also result in an increase in the resistance [5]. Crystals can also exhibit anomalously high starting resistance when the crystal surfaces possess such imperfections as scratches and particulate contamination. Under such conditions, the resistance at low drive levels can be high enough for an oscillator to be unable to start when power is applied. The drive

level dependence of resistance is illustrated in Figure 9. In addition to the nonlinear effects, a high drive level can also cause a frequency change due to a temperature increase caused by the energy dissipation in the active area of the resonator.

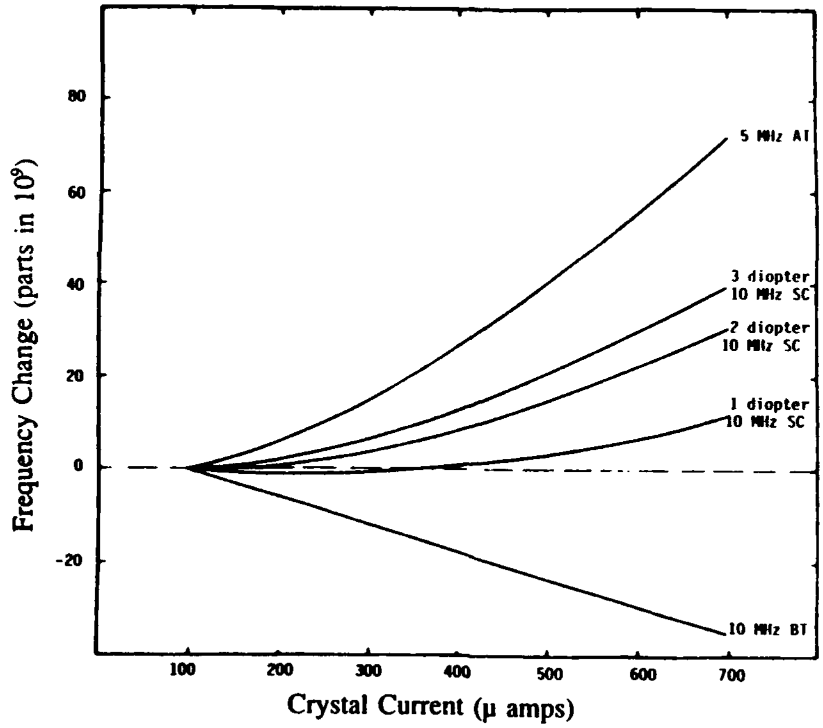


Figure 8. Drive level dependence of frequency.

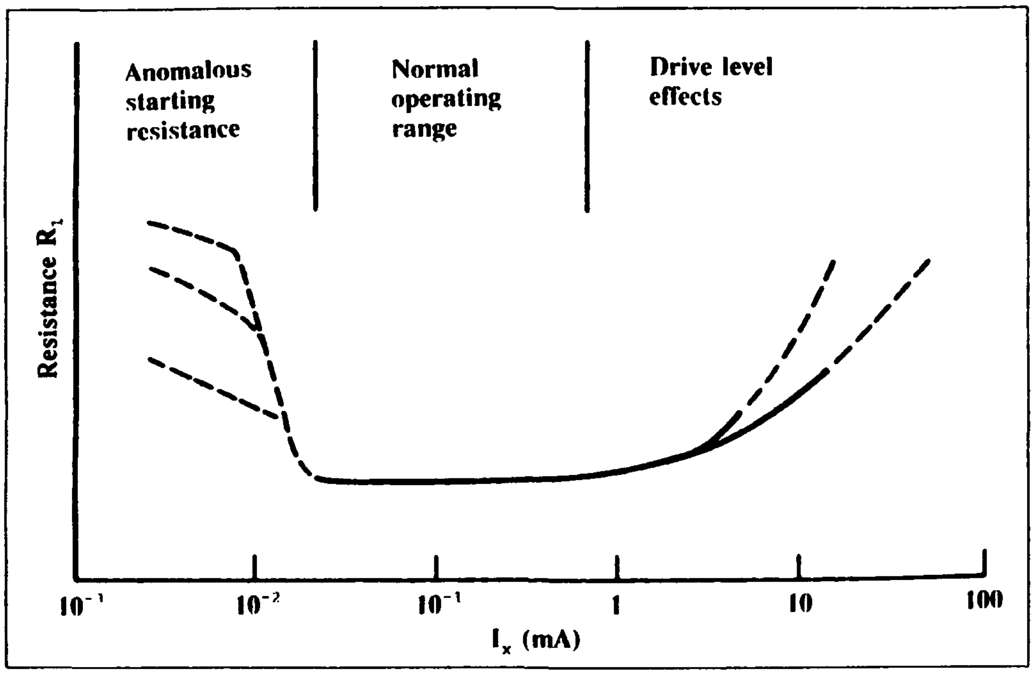


Figure 9. Drive level dependence of crystal unit resistance.

Bulk-acoustic-wave quartz resonators are available in the frequency range of about 1 kHz to 500 MHz. Surface-acoustic-wave (SAW) quartz resonators are available in the range of about 150 MHz to 1.5 GHz. To cover the wide range of frequencies, different cuts, vibrating in a variety of modes, are used. The bulk wave modes of motion are shown in Figure 10. The AT-cut and SC-cut crystals vibrate in a thickness-shear mode. Although the desired thickness-shear mode usually exhibits the lowest resistance, the mode spectrum of even properly designed crystal units exhibits unwanted modes above the main mode. The unwanted modes, also called "spurious modes" or "spurs," are especially troublesome in filter crystals, in which "energy trapping rules" are employed to maximize the suppression of unwanted modes [4]. These rules specify certain electrode geometry to plate geometry relationships. In oscillator crystals, the unwanted modes may be suppressed sufficiently by providing a large enough plate diameter to electrode diameter ratio, or by contouring (i.e., generating a spherical curvature on one or both sides of the plate).

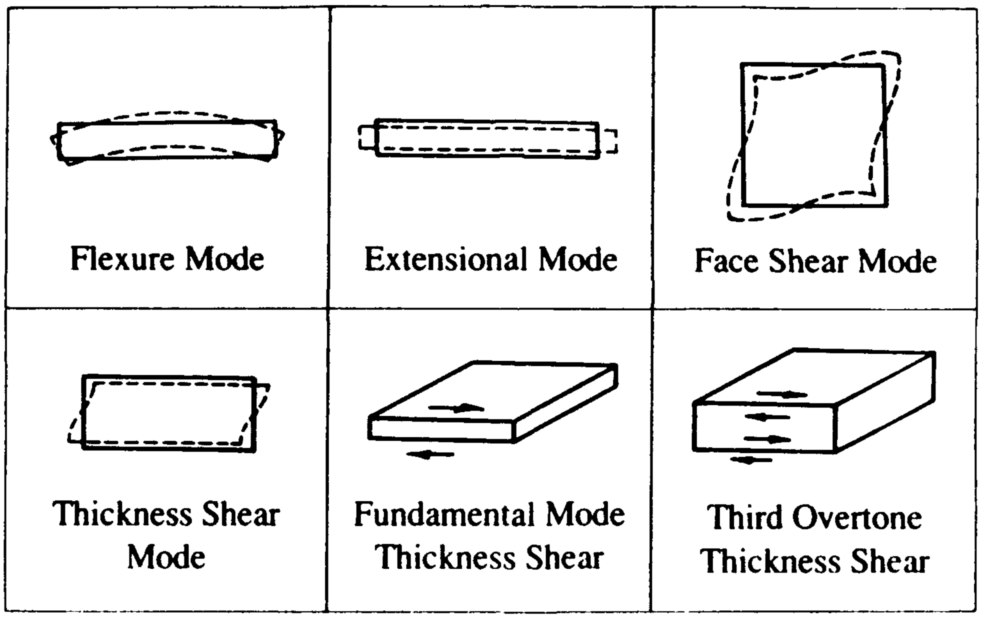


Figure 10. Modes of motion of a quartz resonator.

Above 1 MHz, the AT-cut is commonly used. For high-precision applications, the SC-cut has important advantages over the AT-cut. The AT-cut and SC-cut crystals can be manufactured for fundamental-mode operation up to a frequency of about 300 MHz. (Higher than 1 GHz units have been produced on an experimental basis.) Above 100 MHz, overtone units that operate at a selected harmonic mode of vibration are generally used, although higher than 100 MHz fundamental mode units can be manufactured by means of chemical polishing (etching) techniques [12]. Below 1 MHz, tuning forks, X-Y and NT bars (flexure mode), +5° X-cuts (extensional mode), or CT-cut and DT-cut units (face shear mode) can be used. Tuning forks have become the dominant type of low-

frequency units due to their small size and low cost. Hundreds of millions of quartz tuning forks are produced annually for quartz watches and other applications.

B. Oscillator Categories

A crystal unit's resonance frequency varies with temperature. Typical frequency vs. temperature (*f* vs. *T*) characteristics for crystals used in frequency standards are shown in Figure 11. The three categories of crystal oscillators, based on the method of dealing with the crystal unit's *f* vs. *T* characteristic, are XO, TCXO, and OCXO, (see Figure 12). A simple XO does not contain means for reducing the crystal's *f* vs. *T* variation. A typical XO's f vs. T stability may be ±25 ppm for a temperature range of -55°C to +85°C.

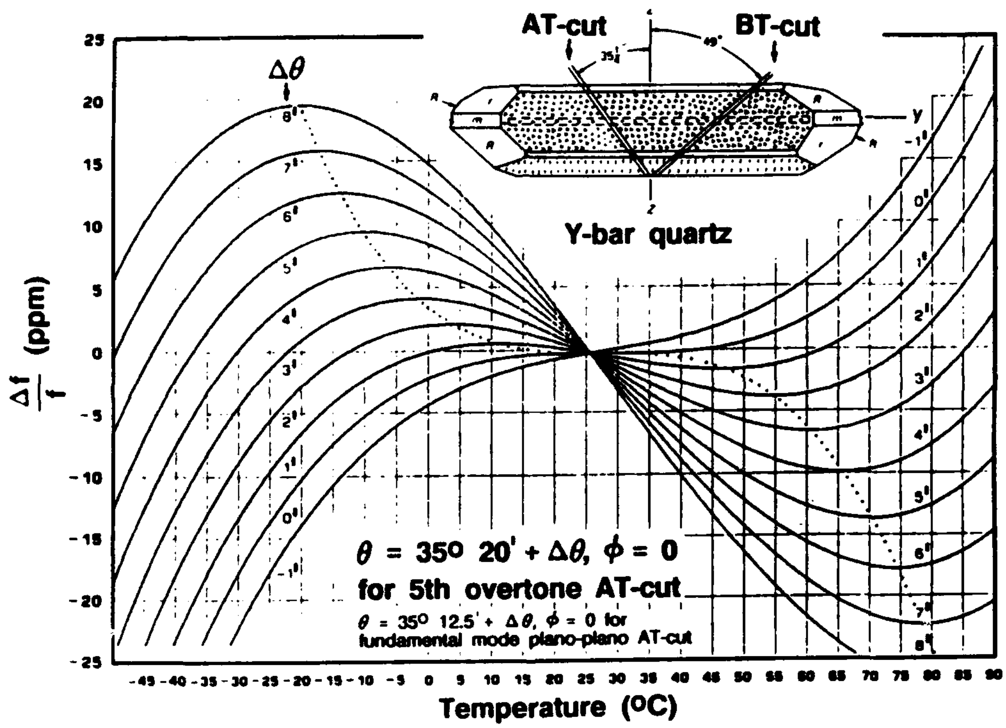


Figure 11. Frequency versus temperature characteristics of AT-cut crystals, showing AT- and BT-cut plates in Y-bar quartz.

In a TCXO, the output signal from a temperature sensor (a *thermistor*) is used to generate a correction voltage that is applied to a voltage-variable reactance (a *varactor*) in the crystal network [13]. The reactance variations produce frequency changes that are equal and opposite to the frequency changes resulting from temperature changes; in other words, the reactance variations compensate for the crystal's *f* vs. *T* variations. Analog TCXOs can provide about a 20-fold improvement over the crystal's *f* vs. T variation. A good TCXO may have an *f* vs. *T* stability of ±1 ppm for a temperature range of -55°C to +85°C.

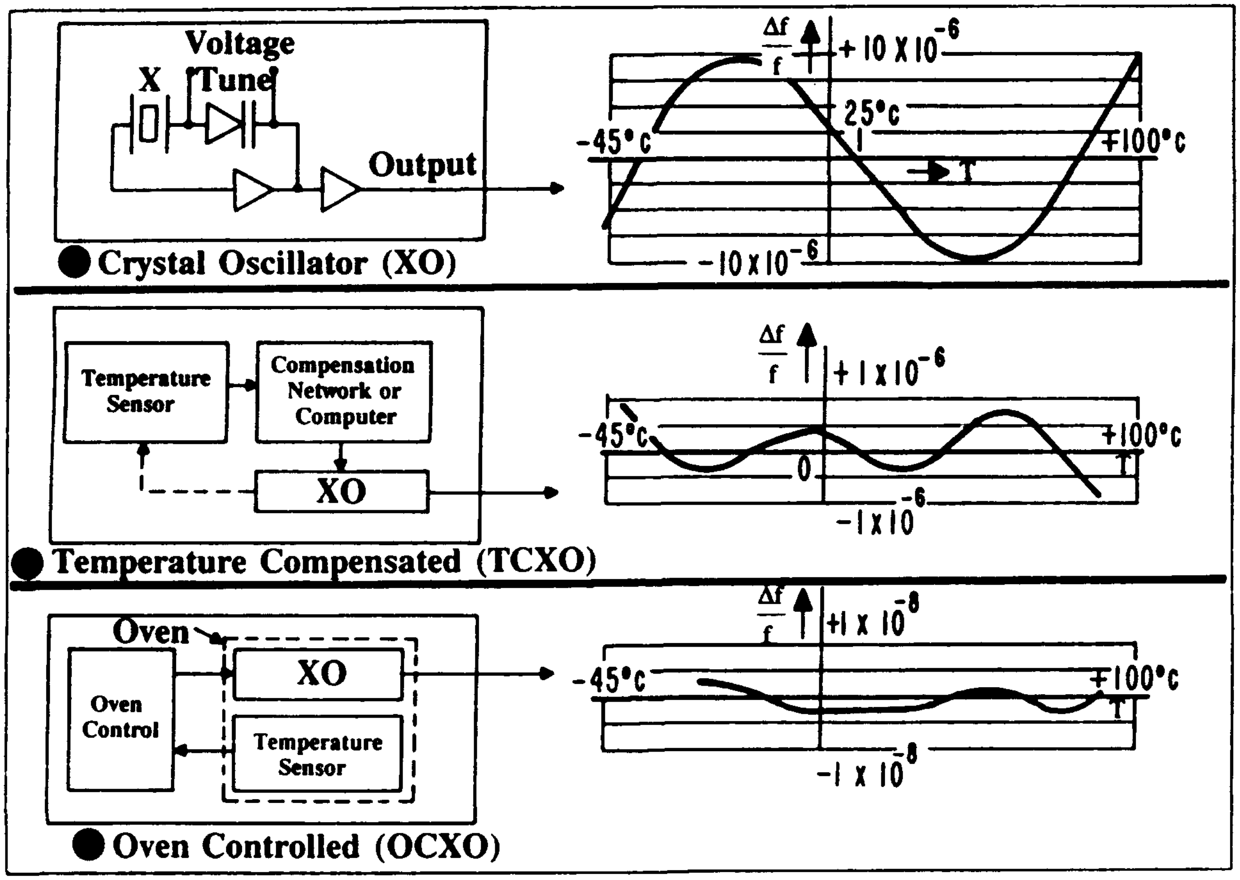


Figure 12. Crystal oscillator categories based on the crystal unit's frequency versus temperature characteristic.

In an OCXO, the crystal unit and other temperature sensitive components of the oscillator circuit are maintained at a constant temperature in an oven [13]. The crystal is manufactured to have an *f* vs. *T* characteristic which has zero slope at the oven temperature. To permit the maintenance of a stable oven temperature throughout the OCXO's temperature range (without an internal cooling means), the oven temperature is selected to be above the maximum operating temperature of the OCXO. OCXOs can provide more than a 1000-fold improvement over the crystal's *f* vs. *T* variation. A good OCXO may have an *f* vs. *T* stability of better than $\pm 5 \times 10^{-9}$ for a temperature range of -55°C to +85°C. OCXOs require more power, are larger, and cost more than TCXOs.

A special case of a compensated oscillator is the microcomputer-compensated crystal oscillator (MCXO) [14]. The MCXO overcomes the two major factors that limit the stabilities achievable with TCXOs: thermometry and the stability of the crystal unit. Instead of a thermometer that is external to the crystal unit, such as a thermistor, the MCXO uses a much more accurate "self-temperature sensing" method. Two modes of

the crystal are excited simultaneously in a dual-mode oscillator. The two modes are combined such that the resulting beat frequency is a monotonic (and nearly linear) function of temperature. The crystal thereby senses its own temperature. To reduce the *f* vs. *T* variations, the MCXO uses digital compensation techniques: pulse deletion in one implementation, and direct digital synthesis of a compensating frequency in another. The frequency of the crystal is not "pulled," which allows the use of high-stability (small C_1) SC-cut crystal units. A typical MCXO may have an *f* vs. *T* stability of $\pm 2 \times 10^{-8}$ for a temperature range of -55°C to +85°C.

C. Oscillator Circuit Types

Of the numerous oscillator circuit types, three of the more commonly discussed ones, the Pierce, the Colpitts, and the Clapp, consist of the same circuit except that the rf ground points are at different locations, as shown in Figure 13. The Butler and modified Butler are also similar to each other; in each, the emitter current is the crystal current. The gate oscillator is a Pierce-type that uses a logic gate plus a resistor in place of the transistor in the Pierce oscillator. (Some gate oscillators use more than one gate.)

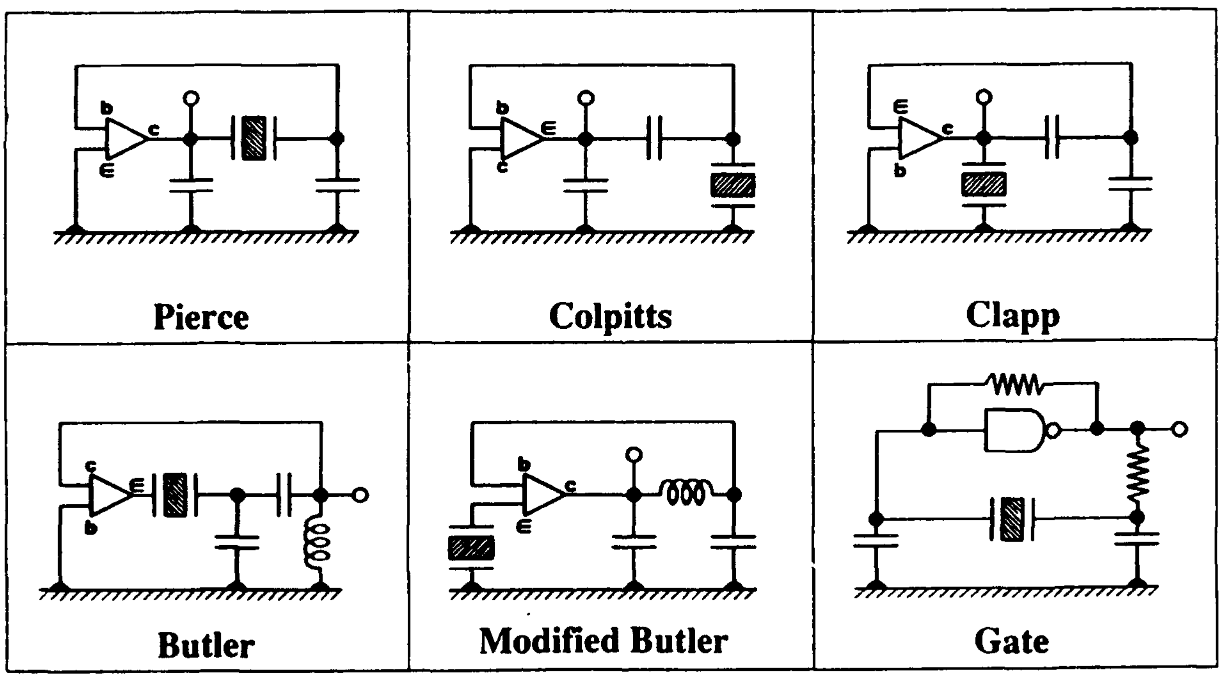


Figure 13. Oscillator circuit types.

Information on designing crystal oscillators can be found in references 1, 2, 5, and 7. The choice of oscillator circuit type depends on factors such as the desired frequency stability, input voltage and power, output power and waveform, tunability, design complexity, cost, and the crystal unit's characteristics.

In the Pierce family, the ground point location has a profound effect on the performance. The Pierce configuration is generally superior to the others, e.g., with respect to the effects of stray reactances and biasing resistors, which appear mostly across the capacitors in the circuit rather than the crystal unit. It is one of the most widely used circuits for high stability oscillators. In the Colpitts configuration, a larger part of the strays appears across the crystal, and the biasing resistors are also across the crystal, which can degrade performance. The Clapp is seldom used because, since the collector is tied directly to the crystal, it is difficult to apply a dc voltage to the collector without introducing losses or spurious oscillations. The Pierce family usually operates at "parallel resonance" (see Figure 4), although it can be designed to operate at series resonance by connecting an inductor in series with the crystal. The Butler family usually operates at (or near) series resonance. The Pierce can be designed to operate with the crystal current above or below the emitter current. Gate oscillators are common in digital systems when high stability is not a major consideration. (See the references for more details on oscillator circuits.)

Most users require a sine wave, or a TTL-compatible, or a CMOS-compatible, or an ECL-compatible output. The latter three can be simply generated from a sine wave. The four output types are illustrated in Figure 14, with the dashed lines representing the supply voltage inputs, and the bold solid lines, the outputs. (There is no "standard" input voltage for sine wave oscillators, and the input voltage for CMOS typically ranges from 5V to 15V.)

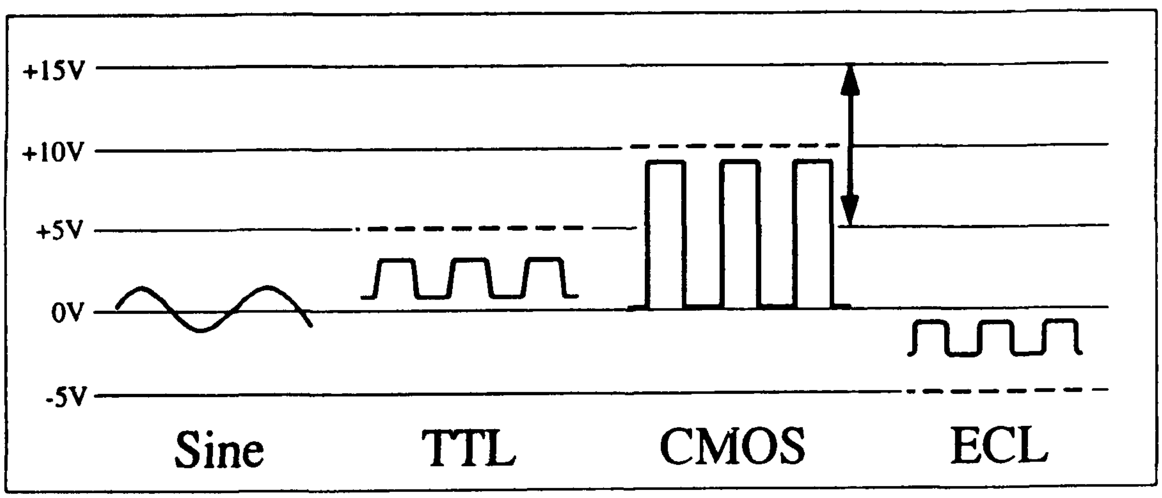


Figure 14. Oscillator outputs.

III. Oscillator Instabilities

A. Accuracy, Stability and Precision

Oscillators exhibit a variety of instabilities. These include aging, noise, and frequency changes with temperature, acceleration, ionizing radiation, power supply voltage, etc. The terms *accuracy*, *stability*, and *precision* are often used in describing an oscillator's quality with respect to its instabilities. Figure 15 illustrates the meanings of these terms for a marksman and for a frequency source. (For the marksman, each bullet hole's distance to the center of the target is the "measurement.")

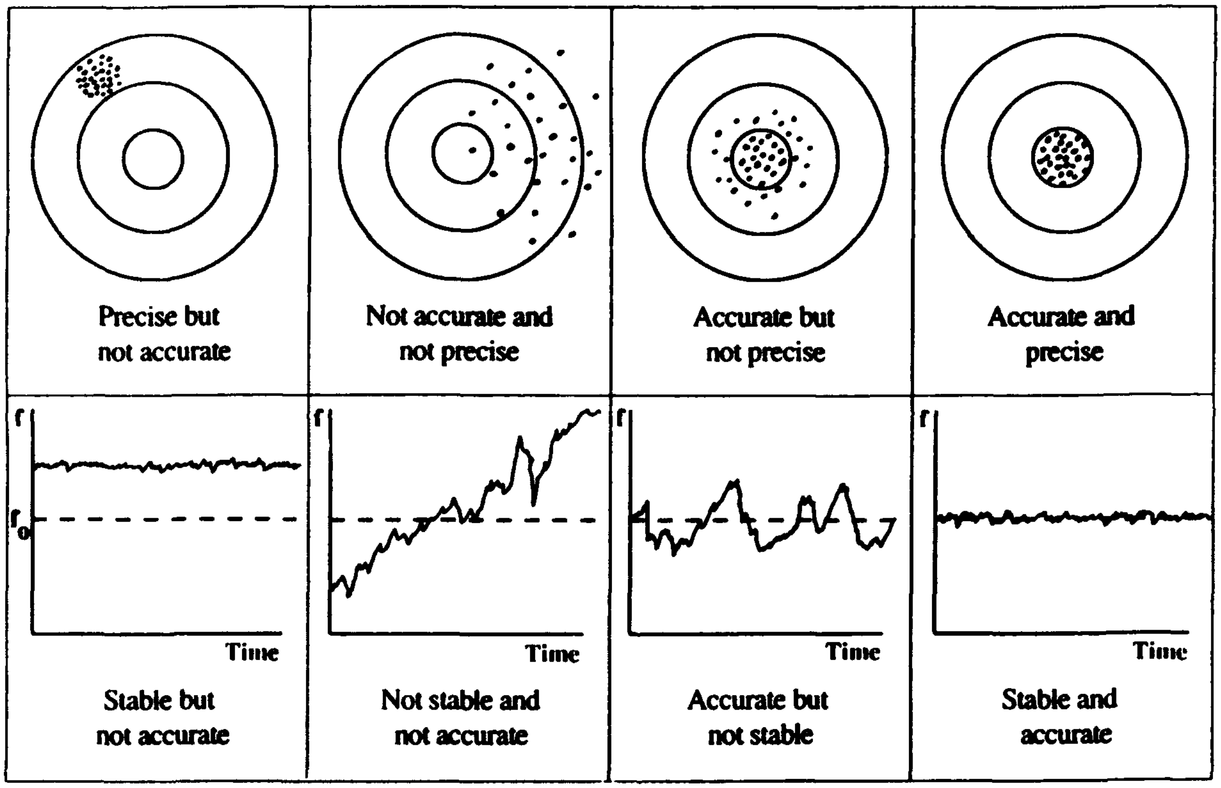


Figure 15. Accuracy, stability and precision examples for a marksman, *top*, and for a frequency source, *bottom*.

Accuracy is the extent to which a given measurement, or the average of a set of measurements for one sample, agrees with the definition of the quantity being measured. It is the degree of "correctness" of a quantity. Frequency standards have varying degrees of accuracy. The International System (SI) of units for time and frequency (second and Hz, respectively) are obtained in laboratories using very accurate frequency standards called *primary* standards. A primary standard operates at a frequency calculable in terms

of the SI definition of the second: "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium atom 133" [15].

Reproducibility is the ability of a single frequency standard to produce the same frequency, without adjustment, each time it is put into operation. From the user's point of view, once a frequency standard is calibrated, reproducibility confers the same advantages as accuracy. *Stability* describes the amount something changes as a function of parameters such as time, temperature, shock, and the like. *Precision* is the extent to which a given set of measurements of one sample agrees with the mean of the set. (A related meaning of the term is used as a descriptor of the quality of an instrument, as in a "precision instrument." In that context, the meaning is usually defined as accurate and precise, although a precision instrument can also be inaccurate and precise, in which case the instrument needs to be calibrated.)

B. Aging

"Aging" and "drift" have occasionally been used interchangeably in the literature. However, recognizing the "need for common terminology for the unambiguous specification and description of frequency and time standard systems," the International Radio Consultative Committee (CCIR) adopted a glossary of terms and definitions in 1990 [16]. According to this glossary, *aging* is "the systematic change in frequency with time due to internal changes in the oscillator," and drift is "the systematic change in frequency with time of an oscillator." *Drift* is due to aging *plus changes in the environment* and other factors external to the oscillator. Aging, not drift, is what one denotes in a specification document and what one measures during oscillator evaluation. Drift is what one observes in an application. For example, the drift of an oscillator in a spacecraft might be due to (the algebraic sum of) aging and frequency changes due to radiation, temperature changes in the spacecraft, and power supply changes.

Aging can be positive or negative [17]. Occasionally, a reversal in aging direction is observed. At a constant temperature, aging usually has an approximately logarithmic dependence on time. Typical (computer-simulated) aging behaviors are illustrated in Figure 16, where A(t) is a logarithmic function and B(t) is the same function but with different coefficients. The curve showing the reversal is the sum of the other two curves. A reversal indicates the presence of at least two aging mechanisms. The aging rate of an oscillator is highest when it is first turned on. When the temperature of a crystal unit is changed (e.g., when an OCXO is turned off and turned on at a later time), a new aging cycle starts. (See the section concerning hysteresis and retrace below for additional discussion of the effects of temperature cycling.)

The primary causes of crystal oscillator aging are stress relief in the mounting structure of the crystal unit, mass transfer to or from the resonator's surfaces due to adsorption or desorption of contamination, changes in the oscillator circuitry, and,

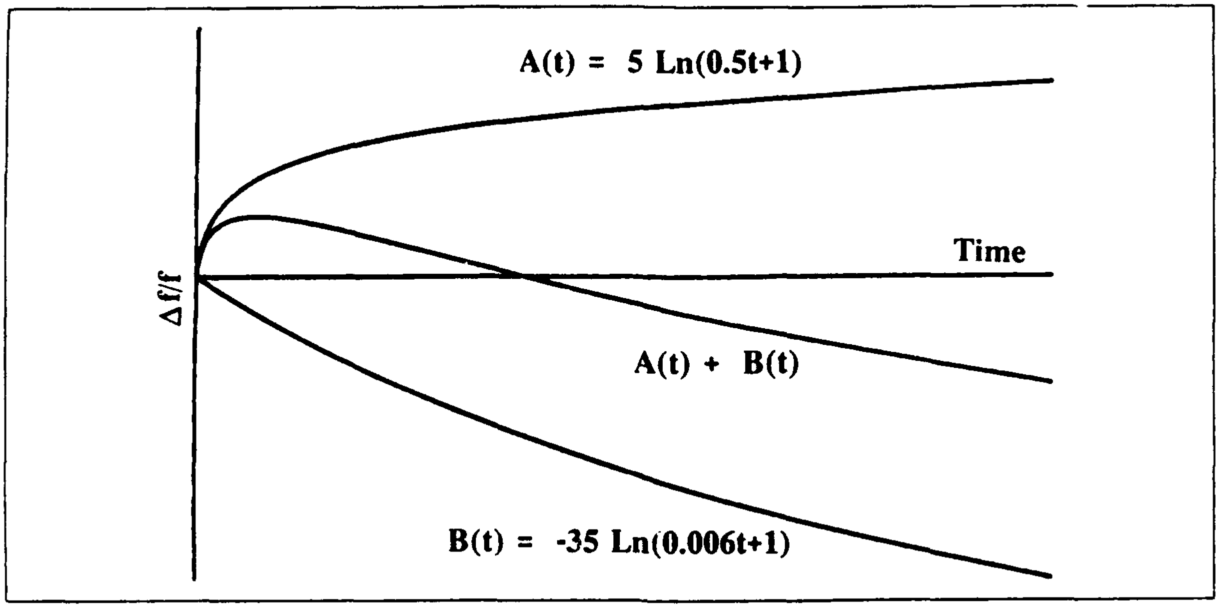


Figure 16. Computer-simulated typical aging behaviors; where A(t) and B(t) are logarithmic functions with different coefficients.

possibly, changes in the quartz material. Because the frequency of a thickness-shear crystal unit, such as an AT-cut or an SC-cut, is inversely proportional to the thickness of the crystal plate, and because a typical 5-MHz plate is on the order of 1 million atomic layers thick, the adsorption or desorption of contamination equivalent to the mass of one atomic layer of quartz changes the frequency by about 1 ppm. Therefore, in order to achieve low aging, crystal units must be fabricated and hermetically sealed in an ultraclean, ultra-high-vacuum environment. As of 1992, the aging rates of typical commercially available crystal oscillators range from 5 ppm to 10 ppm per year for an inexpensive XO, to 0.5 ppm to 2 ppm per year for a TCXO, and to 0.05 ppm to 0.1 ppm per year for an OCXO. The highest precision OCXOs can age a few parts in 10^{12} per day, i.e., less than 0.01 ppm per year.

C. Noise in Frequency Standards

1. The Effects of Noise

Sometimes the suitability of oscillators for an application is limited by deterministic phenomena. In other instances, stochastic (random) processes establish the performance limitations. Except for vibration, the short-term instabilities almost always result from noise. Long-term performance of quartz and rubidium standards is limited primarily

by the temperature sensitivity and the aging, but the long-term performance of cesium and some hydrogen standards is limited primarily by random processes.

Noise can have numerous adverse effects on system performance. Among these effects are the following: (1) it limits the ability to determine the current state and the predictability of precision oscillators (e.g., the noise of an oscillator produces time prediction errors of ~ $\tau\sigma_y(\tau)$ for prediction intervals of τ); (2) it limits synchronization and syntonization accuracies; (3) it can limit a receiver's useful dynamic range, channel spacing, and selectivity; (4) it can cause bit errors in digital communications systems; (5) it can cause loss of lock, and limit acquisition and reacquisition capability in phase-locked-loop systems; and (6) it can limit radar performance, especially Doppler radar.

It is important to have appropriate statistical measures to characterize the random component of oscillator instability. The subject of noise characterization has been reviewed [4,18] and is also the subject of an IEEE standard [19]. The two-sample deviation, denoted by $\sigma_y(\tau)$, is the measure of short-term instabilities in the time domain. The phase noise, denoted by $\mathcal{L}(f)$, or the phase instability, denoted by $S_\phi(f)$, are measures of instabilities in the frequency domain; $\mathcal{L}(f) \equiv \frac{1}{2}S_\phi(f)$ [19].

2. Noise in Crystal Oscillators

Although the causes of noise in crystal oscillators are not fully understood, several causes of short-term instabilities have been identified. Temperature fluctuations can cause short-term instabilities via thermal-transient effects (see the section below concerning dynamic *f* vs. *T* effects), and via activity dips at the oven set point in OCXOs. Other causes include Johnson noise in the crystal unit, random vibration (see the section below concerning acceleration effects in crystal oscillators), noise in the oscillator circuitry (both the active and passive components can be significant noise sources), and fluctuations at various interfaces on the resonator (e.g., in the number of molecules adsorbed on the resonator's surface).

In a properly designed oscillator, the resonator is the primary noise source close to the carrier and the oscillator circuitry is the primary source far from the carrier. The noise close to the carrier (i.e., within the bandwidth of the resonator) has a strong inverse relationship with resonator *Q*, such that $\mathcal{L}(f) \propto 1/Q^4$. In the time domain, $\sigma_y(\tau) \approx (2 \times 10^{-7})/Q$ at the noise floor. In the frequency domain, the noise floor is limited by Johnson noise, the noise power of which is kT = -174 dBm/Hz at 290°K. A higher signal (i.e., a higher resonator drive current) will improve the noise floor but not the close-in noise. In fact, for reasons that are not understood fully, above a certain point, higher drive levels usually degrade the close-in noise. For example, the maximum "safe" drive level is about 100 μa for a 5-MHz fifth overtone AT-cut resonator with $Q \approx 2.5$ million. The safe drive current can be substantially higher for high-frequency SC-cut resonators. For example, $\mathcal{L}(f)$ = -180 dBc/Hz has been achieved with 100-MHz fifth overtone SC-cut resonators at

drive currents ≈ 10 mA. However, such a noise capability is useful only in a vibration-free laboratory environment. If there is even a slight amount of vibration at the offset frequencies of interest, the vibration-induced noise will dominate the quiescent noise of the oscillator (see the section below concerning acceleration effects in crystal oscillators).

When low noise is required in the microwave (or higher) frequency range, SAW oscillators and dielectric resonator oscillators (DROs) are sometimes used. When compared with multiplied-up (bulk-acoustic-wave) quartz oscillators, these oscillators can provide lower noise far from the carrier at the expense of poorer noise close to the carrier, poorer aging, and poorer temperature stability. SAW oscillators and DROs can provide lower noise far from the carrier because these devices can be operated at higher drive levels, thereby providing higher signal-to-noise ratios, and because the devices operate at higher frequencies, thereby reducing the "20 log N" losses due to frequency multiplication by *N*. $\mathcal{L}(f)$ = -180 dBc/Hz noise floors have been achieved with state-of-the-art SAW oscillators [20]. Of course, as is the case for high-frequency bulk-wave oscillators, such noise floors are realizable only in environments that are free of vibrations at the offset frequencies of interest. Figures 17 and 18 show comparisons of state-of-the-art 5 MHz and 100 MHz BAW oscillators and a 500 MHz SAW oscillator, multiplied to 10 GHz. Figure 17 shows the comparison in a quiet environment, and Figure 18 shows it in a vibrating environment.

D. Frequency versus Temperature Stability

1. Static Frequency versus Temperature Stability

As an illustration of the effects that temperature can have on frequency stability, Figure 19 shows the effects of temperature on the accuracy of a typical quartz wristwatch. Near the wrist temperature, the watch can be very accurate because the frequency of the crystal (i.e., the clock rate) changes very little with temperature. However, when the watch is cooled to -55°C or heated to +100°C, it loses about 20 seconds per day, because the typical temperature coefficient of frequency of the tuning fork crystals used in quartz watches is -0.035 ppm/°C^2.

The static *f* vs. *T* characteristics of crystal units are determined primarily by the angles of cut of the crystal plates with respect to the crystallographic axes of quartz [3-5]. "Static" means that the rate of change of temperature is slow enough for the effects of temperature gradients (explained later) to be negligible. As Figure 11 illustrates for the AT-cut, a small change in the angle of cut (seven minutes in the illustration) can significantly change the *f* vs. *T* characteristics. The points of zero temperature coefficient, the "turnover points," can be varied over a wide range by varying the angles of cut. The *f* vs. *T* characteristics of SC-cut crystals are similar to the curves shown in Figure 11, with the inflection temperature (T_i) shifted to about 95°C. (The exact value of T_i depends on the resonator's design.)

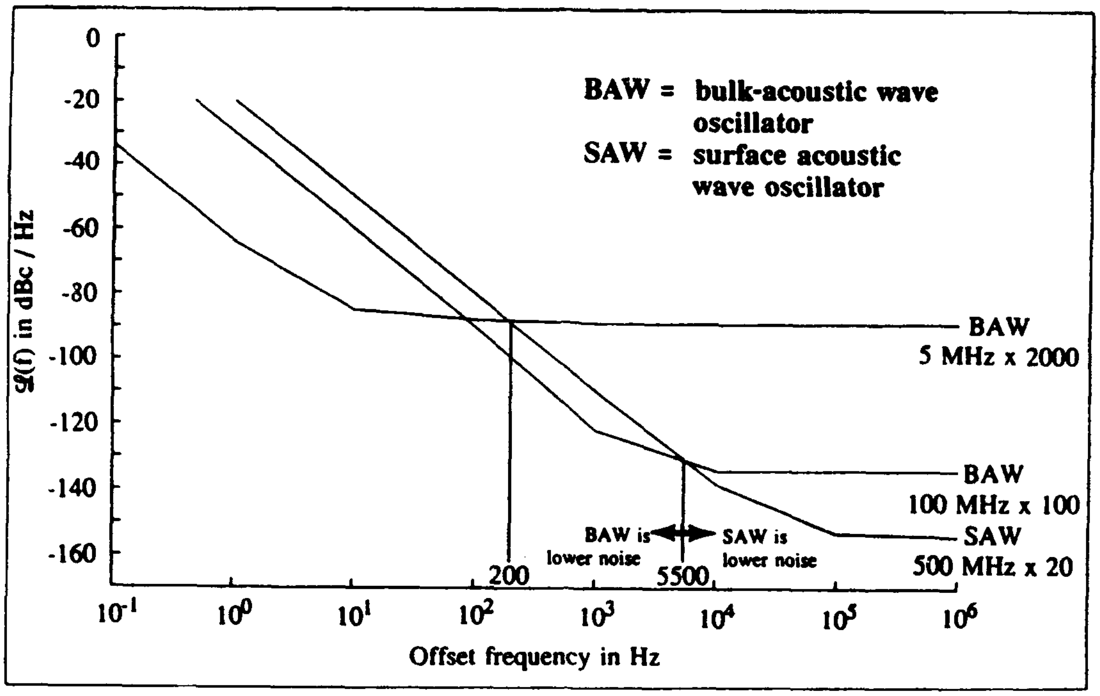


Figure 17. Low-noise SAW and BAW multiplied to 10 GHz (in a nonvibrating environment).

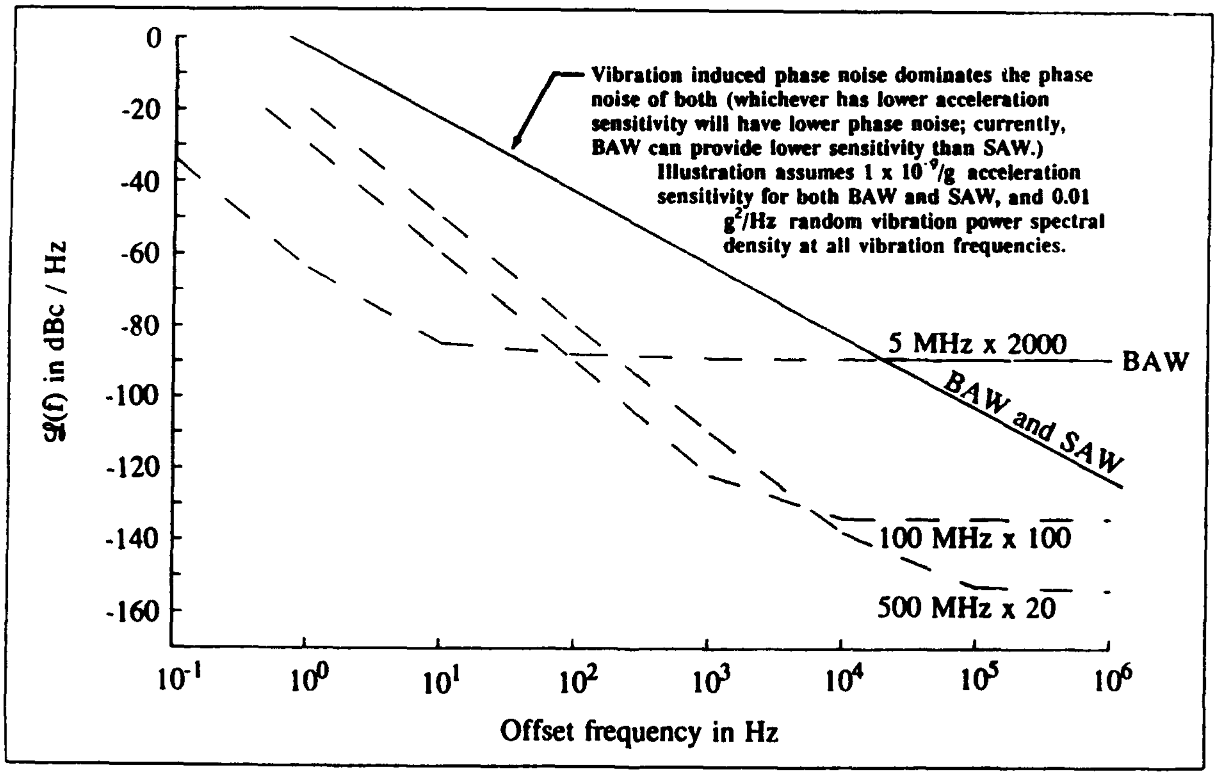


Figure 18. Low-noise SAW and BAW multiplied to 10 GHz (in a vibrating environment).

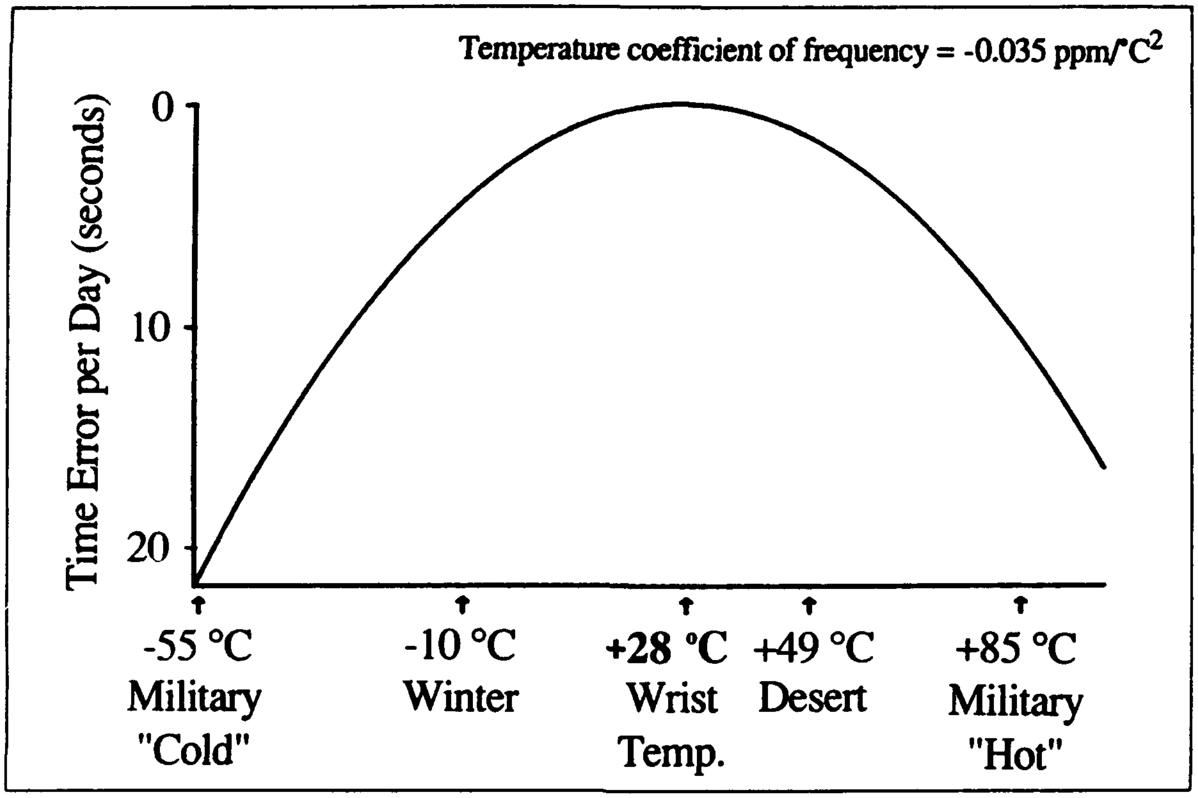


Figure 19. Wristwatch accuracy as it is affected by temperature.

Other factors that can affect the *f* vs. *T* characteristics of crystal units include the overtone [21]; the geometry of the crystal plate; the size, shape, thickness, density and stresses of the electrodes; the drive level; impurities and strains in the quartz material; stresses in the mounting structure; interfering modes; ionizing radiation; the rate of change of temperature (i.e., thermal gradients) [22]; and thermal history. The last two factors are important for understanding the behaviors of OCXOs and TCXOs, and are, therefore, discussed separately.

The effect of harmonics, i.e. "overtones," on *f* vs. *T* is illustrated for AT-cut crystals in Figure 20 [21]. This effect is important for understanding the operation of the MCXO. The MCXO contains an SC-cut resonator and a dual mode oscillator that excites both the fundamental mode and the third overtone of the resonator. The difference between the fundamental mode *f* vs. *T* and the third overtone *f* vs. *T* is due almost exclusively to the difference between the first order temperature coefficients. Therefore, when the third overtone frequency is subtracted from three times the fundamental mode frequency, the resulting "beat frequency" is a monotonic and nearly linear function of temperature. This beat frequency enables the resonator to sense its own temperature.

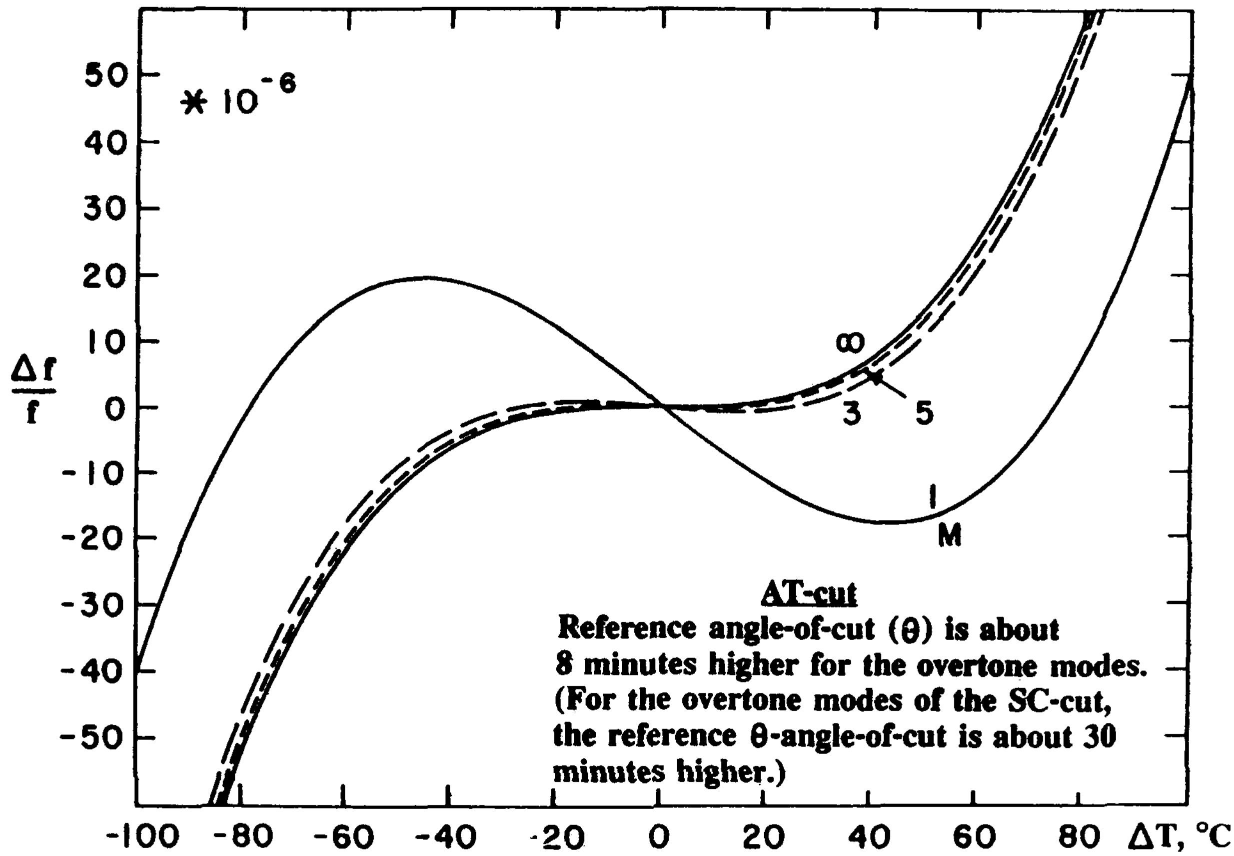


Figure 20. Effects of harmonics on *f vs. T.*

Interfering modes can cause "activity dips" (see Figure 21), which can cause oscillator failure [23] . Near the activity dip temperature, anomalies appear in both the *f* vs. *T* and resistance (*R*) vs. *T* characteristics. When the resistance increases at the activity dip, and the oscillator's gain margin is insufficient, the oscillation stops. Activity dips can be strongly influenced by the crystal's drive level and load reactance. The activity-dip temperature is a function of C_L because the interfering mode usually has a large temperature coefficient and a C_1 that is different from that of the desired mode. Activity dips are troublesome in TCXOs, and also in OCXOs when the dip occurs at the oven temperature. The incidence of activity dips in SC-cut crystals is far lower than in AT-cut crystals.

An important factor that affects the *f* vs. *T* characteristics of crystal oscillators is the load capacitor. When a capacitor is connected in series with the crystal, the *f* vs. *T* characteristic of the combination is rotated slightly from that of the crystal alone. The temperature coefficient of the load capacitor can greatly magnify the rotation [24].

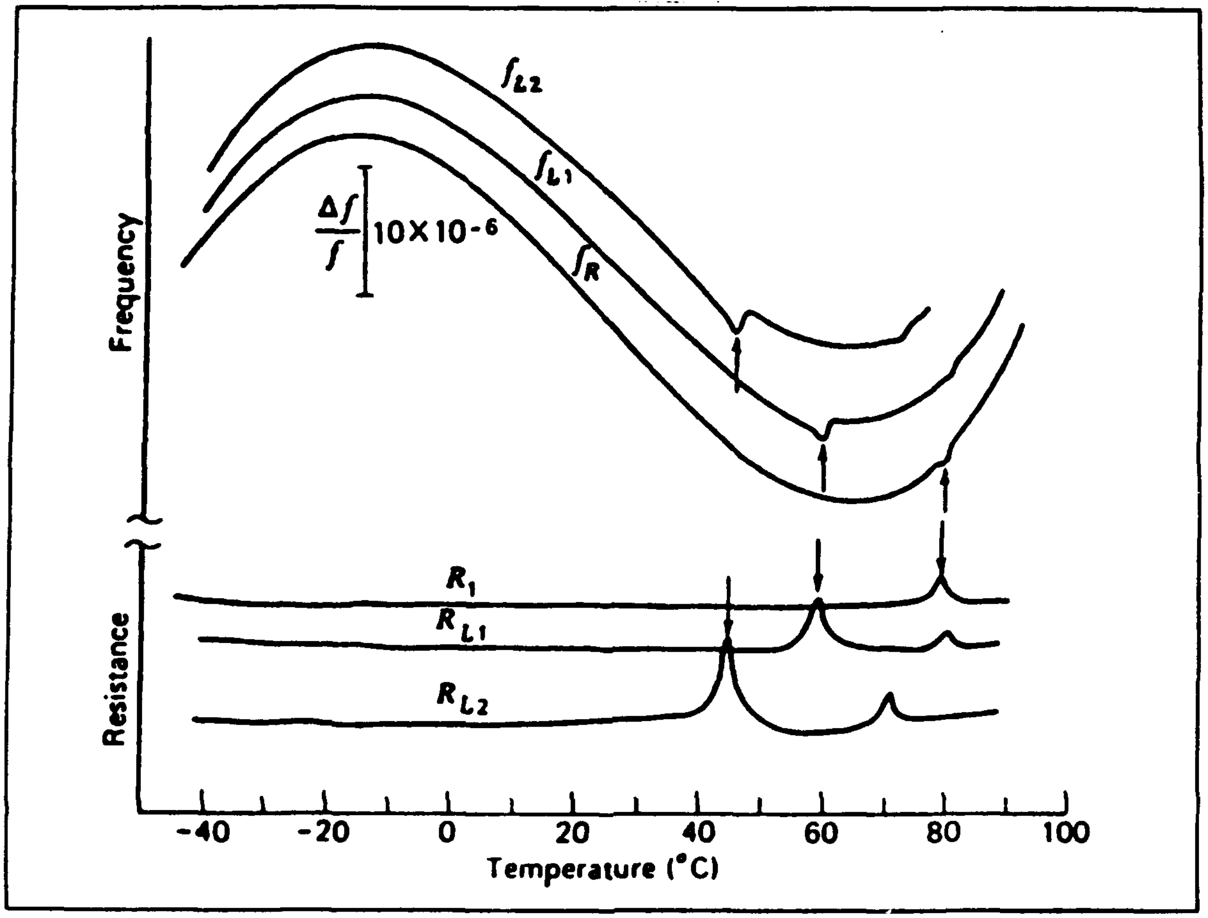


Figure 21. Activity dips in the frequency versus temperature and resistance versus temperature characteristics, with and without C_L.

The *f* vs. *T* of crystals can be described by a polynomial function. A cubic function is usually sufficient to describe the *f* vs. *T* of AT-cut and SC-cut crystals to an accuracy of ±1 ppm. In the MCXO, in order to fit the *f* vs. *T* data to $\pm 1 \times 10^{-8}$, a polynomial of at least seventh order is usually necessary [25].

2. Dynamic Frequency versus Temperature Effects

Changing the temperature surrounding a crystal unit produces thermal gradients when, for example, heat flows to or from the active area of the resonator plate through the mounting clips. The static *f* vs. *T* characteristic is modified by the thermal-transient effect resulting from the thermal-gradient-induced stresses [22]. When an OCXO is turned on, there can be a significant thermal-transient effect. Figure 22 shows what happens to the frequency output of two OCXOs, each containing an oven that reaches

the equilibrium temperature in six minutes. One oven contains an AT-cut, the other, an SC-cut crystal. Thermal gradients in the AT-cut produce a large frequency undershoot that anneals out several minutes after the oven reaches equilibrium. The SC-cut crystal, being "stress-compensated" and thereby insensitive to such thermal-transient-induced stresses, reaches the equilibrium frequency as soon as the oven stabilizes.

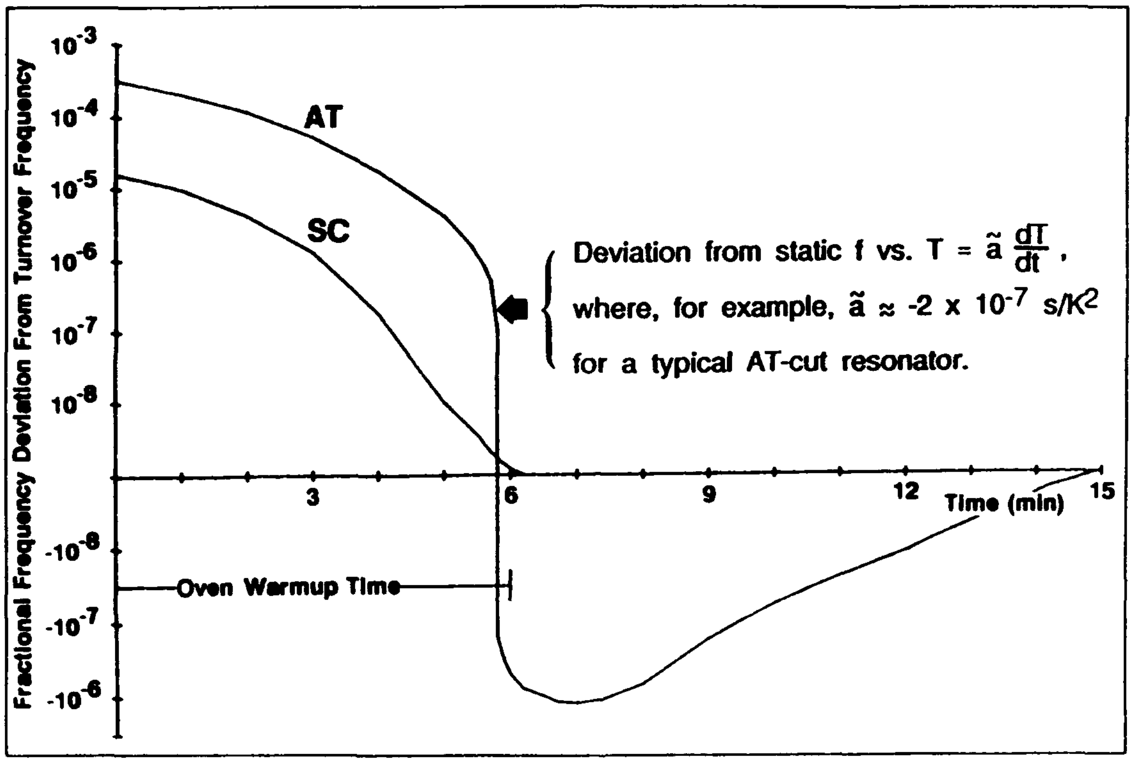


Figure 22. Warm-up characteristics of AT-cut and SC-cut crystal oscillators (OCXOs).

In addition to extending the warmup time of OCXOs, when crystals other than SC-cuts are used, the thermal-transient effect makes it much more difficult to adjust the temperature of OCXO ovens to the desired turnover points, and the OCXO frequencies are much more sensitive to oven-temperature fluctuations [22].

The testing and compensation accuracies of TCXOs are also adversely affected by the thermal-transient effect. As the temperature is changed, the thermal-transient effect distorts the static *f* vs. *T* characteristic, which leads to apparent hysteresis [26]. The faster the temperature is changed, the larger is the contribution of the thermal-transient effect to the *f* vs. *T* performance.

3. Thermal Hysteresis and Retrace

The *f* vs. *T* characteristics of crystal oscillators do not repeat exactly upon temperature cycling [27]. The lack of repeatability in TCXOs, "thermal hysteresis," is illustrated in Figure 23. The lack of repeatability in OCXOs, "retrace," is illustrated in Figure 24. *Hysteresis* is defined [28] as the difference between the up-cycle and the down-cycle *f* vs. *T* characteristics, and is quantified by the value of the difference at the temperature where the difference is maximum. Hysteresis is determined during at least one complete quasistatic temperature cycle between specified temperature limits. *Retrace* is defined as the nonrepeatability of the *f* vs. *T* characteristic at a fixed temperature (which is usually the oven temperature of an OCXO) upon on-off cycling an oscillator under specified conditions.

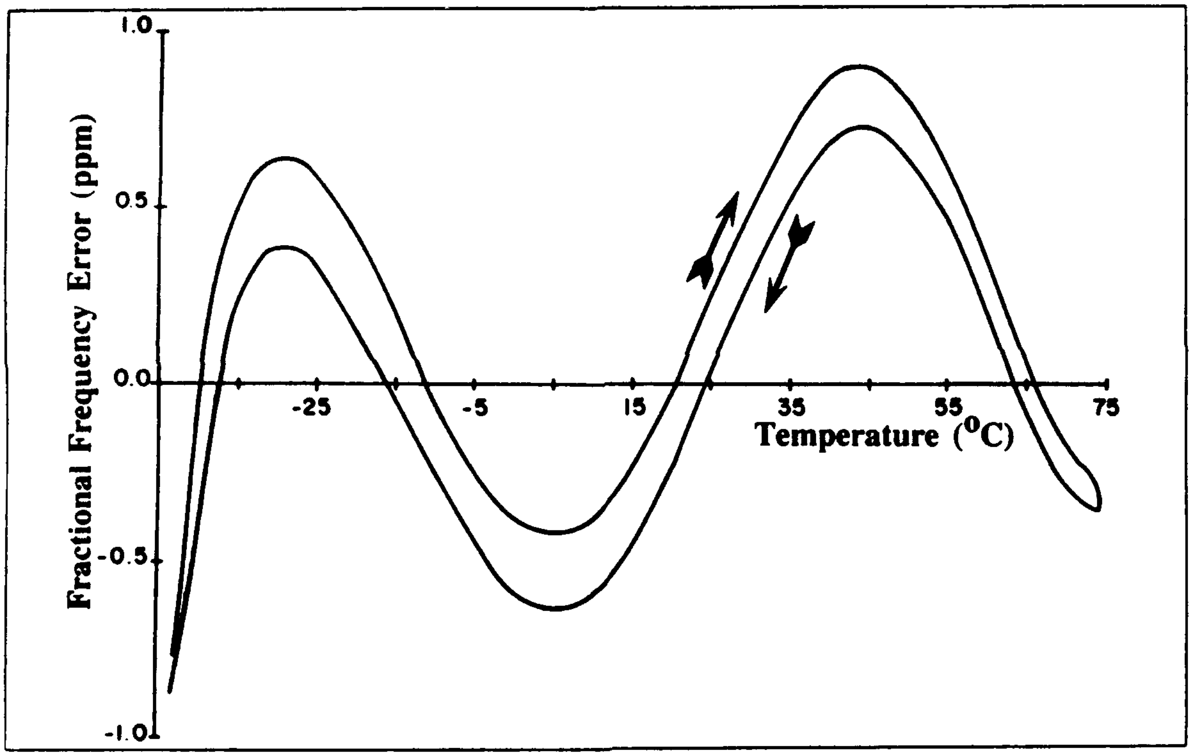


Figure 23. Temperature-compensated crystal oscillator (TCXO) thermal hysteresis, showing that the first f vs. T characteristic upon increasing temperature differs from the characteristic upon decreasing temperature.

Hysteresis is the major factor limiting the stability achievable with TCXOs. It is especially so in the MCXO because, in principle, the digital compensation method used in the MCXO would be capable of compensating for the *f* vs. *T* variations to arbitrary accuracy if the *f* vs. *T* characteristics could be described by single-valued functions.

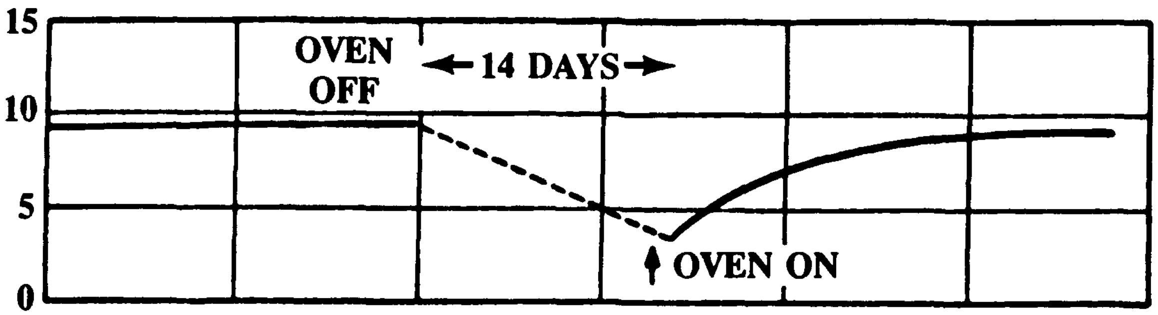


Figure 24. Oven-controlled crystal oscillator (OCXO) retrace example, showing that upon restarting the oscillator after a 14 day off-period, the frequency was about 7×10^{-9} lower than what it was just before turn-off, and that the aging rate had increased significantly upon the restart. About a month elapsed before the pre-turn-off aging rate was reached again. *(Figure shows $\Delta f/f$ in parts in 10^9 vs. time in days.)*

Retrace limits the accuracies achievable with OCXOs in applications where the OCXO is on-off cycled. Typical values of hysteresis in TCXOs range from 1 ppm to 0.1 ppm when the temperature-cycling ranges are 0°C to 60°C, and -55°C to +85°C. Hysteresis of less than 1×10^{-8} has been observed in a few SC-cut (MCXO) resonators [25]. The typical MCXO resonator hysteresis in early models of the MCXO was a few parts in 10^8 [14]. Typical OCXO retrace specifications, after a 24 hour off period at about 25°C, range from 2×10^{-8} to 1×10^{-9}. Low-temperature storage during the off period, and extending the off period, usually make the retrace worse [17].

The causes of hysteresis and retrace are not well understood; the experimental evidence to date is inconclusive [27]. The mechanisms that can cause these effects include strain changes, changes in the quartz, oscillator circuitry changes, contamination redistribution in the crystal enclosure, and apparent hysteresis or retrace due to thermal gradients.

E. Warmup

When power is applied to a frequency standard, it takes a finite amount of time before the equilibrium frequency stability is reached. Figure 22, discussed above, illustrates the warmup of two OCXOs. The warmup time of an oscillator is a function of the thermal properties of the resonator, the oscillator circuit and oven construction, the input power, and the oscillator's temperature prior to turn-on. Typical warmup time specifications of OCXOs (e.g., from a 0°C start) range from 3 minutes to 10 minutes. Even TCXOs, MCXOs, and simple XOs take a few seconds to "warm up," although these are not ovenized. The reasons for the finite warmup, i.e., stabilization, periods are that it takes a finite amount of time for the signal to build up in any high-Q circuit, and the few tens of milliwatts of power which are dissipated in these oscillators can change the thermal conditions within the oscillators.

F. Acceleration Effects

Acceleration changes a crystal oscillator's frequency [29]. The acceleration can be a steady-state acceleration, vibration, shock, attitude change (2-g tipover), or acoustic noise. The amount of frequency change depends on the magnitude and direction of the acceleration $\vec{A}$, and on the acceleration sensitivity of the oscillator $\vec{\Gamma}$. The acceleration sensitivity is a vector quantity. The frequency change can be expressed as

$$\frac{\Delta f}{f} = \vec{\Gamma} \bullet \vec{A} \ .$$

Typical values of $|\vec{\Gamma}|$ are in the range of 10^{-9}/g to 10^{-10}/g. For example, when $\vec{\Gamma} = 2 \times 10^{-9}$/g and is normal to the earth's surface, and the oscillator is turned upside down (a change of 2 g), the frequency changes by 4×10^{-9}. When this oscillator is vibrated in the up-and-down direction, the time dependent acceleration modulates the oscillator's output frequency at the vibration frequency, with an amplitude of 2×10^{-9}/g.

When an oscillator is rotated 180° about a horizontal axis, the scalar product of the gravitational field and the unit vector normal to the initial "top" of the oscillator changes from -1g to +1g, i.e., by 2g. Figure 25 shows actual data of the fractional frequency shifts of an oscillator when the oscillator was rotated about three mutually perpendicular axes in the earth's gravitational field. For each curve, the axis of rotation was horizontal. The sinusoidal shape of each curve is a consequence of the scalar product being proportional to the cosine of the angle between the acceleration-sensitivity vector and the acceleration due to gravity [29].

In the frequency domain, the modulation results in vibration-induced sidebands that appear at plus and minus integer multiples of the vibration frequency from the carrier frequency. Figure 26 shows the output of a spectrum analyzer for a 10-MHz, 1.4×10^{-9}/g oscillator that was vibrated at 100 Hz and 10 g. For sinusoidal vibration, the "sidebands" are spectral lines. When the frequency is multiplied, as it is in many applications, the sideband levels increase by 20 dB for each 10X multiplication. The increased sideband power is extracted from the carrier. Under certain conditions of multiplication, the carrier disappears, i.e., all the energy is then in the sidebands.

The acceleration sensitivity can be calculated from the vibration-induced sidebands. The preferred method is to measure the sensitivity at a number of vibration frequencies in order to reveal resonances. Figure 27 shows an example of the consequence of a resonance in an OCXO, at 424 Hz. This resonance amplified the acceleration sensitivity 17-fold.

The effect of random vibration is to raise the phase-noise level of the oscillator. The degradation of phase-noise can be substantial when the oscillator is on a vibrating platform, such as on an aircraft. Figure 28 shows a typical aircraft random-vibration

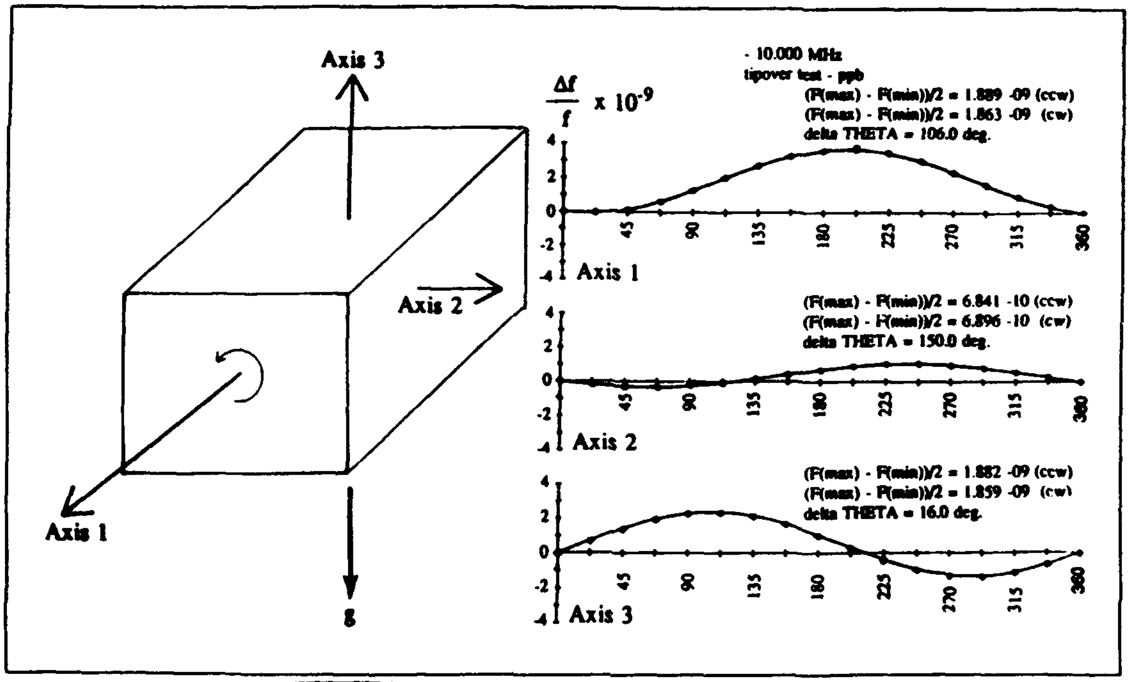


Figure 25. 2-g tipover test (Δf vs. attitude about three axes).

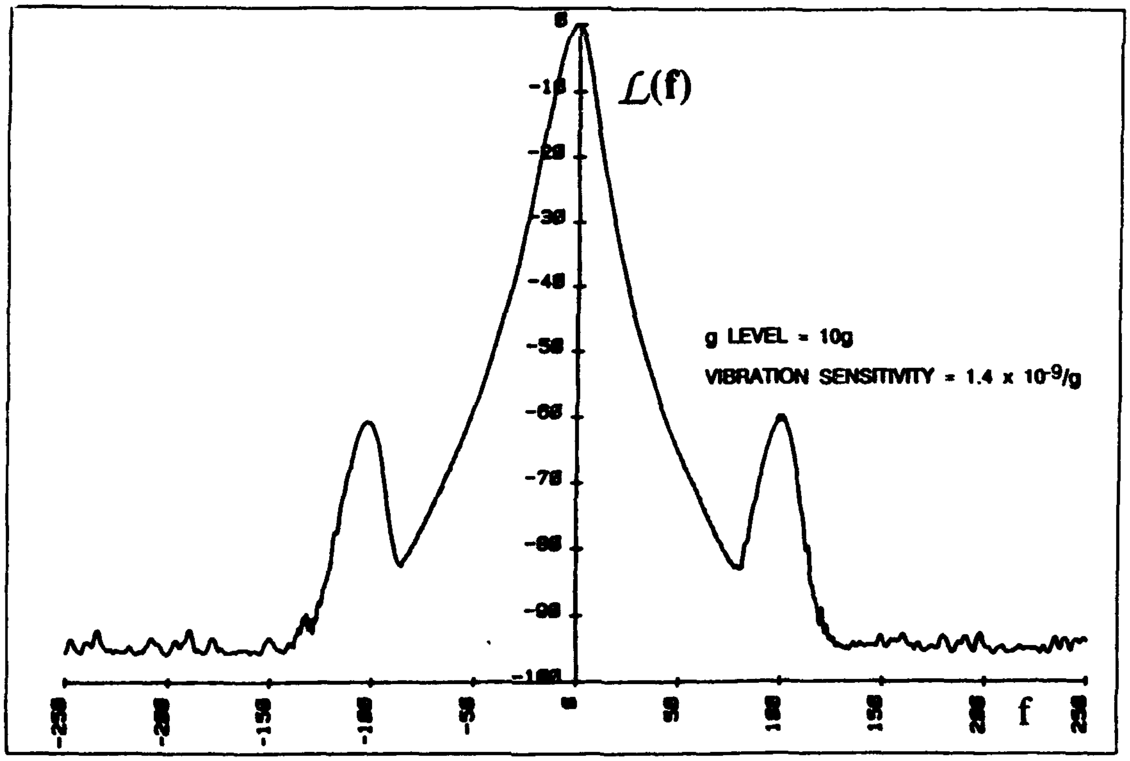


Figure 26. Vibration-induced "sidebands" (i.e., spectral lines).

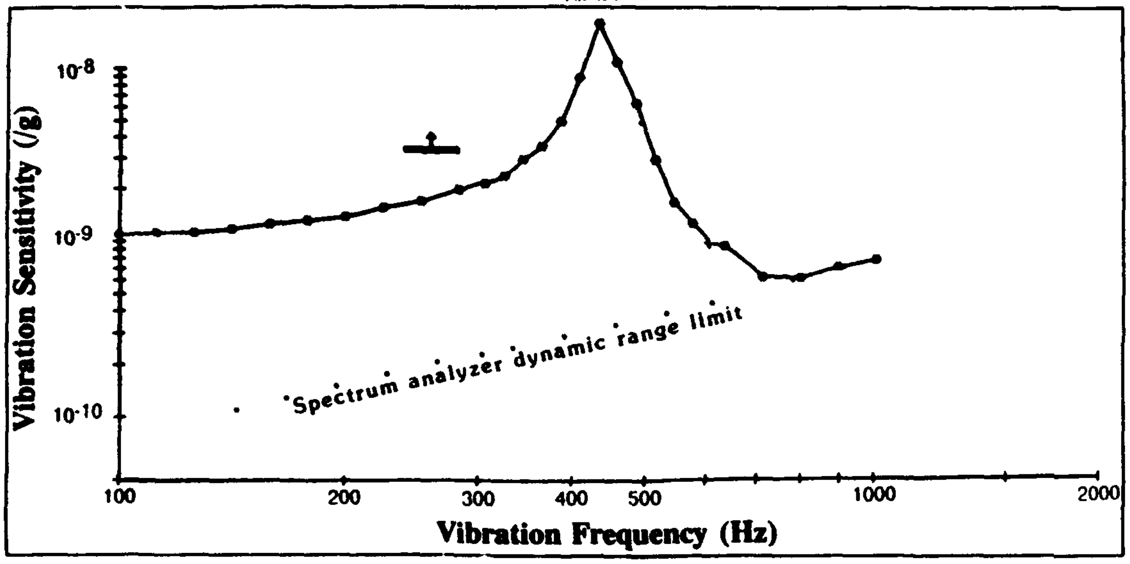


Figure 27. Resonance in the acceleration sensitivity *vs.* vibration frequency characteristic.

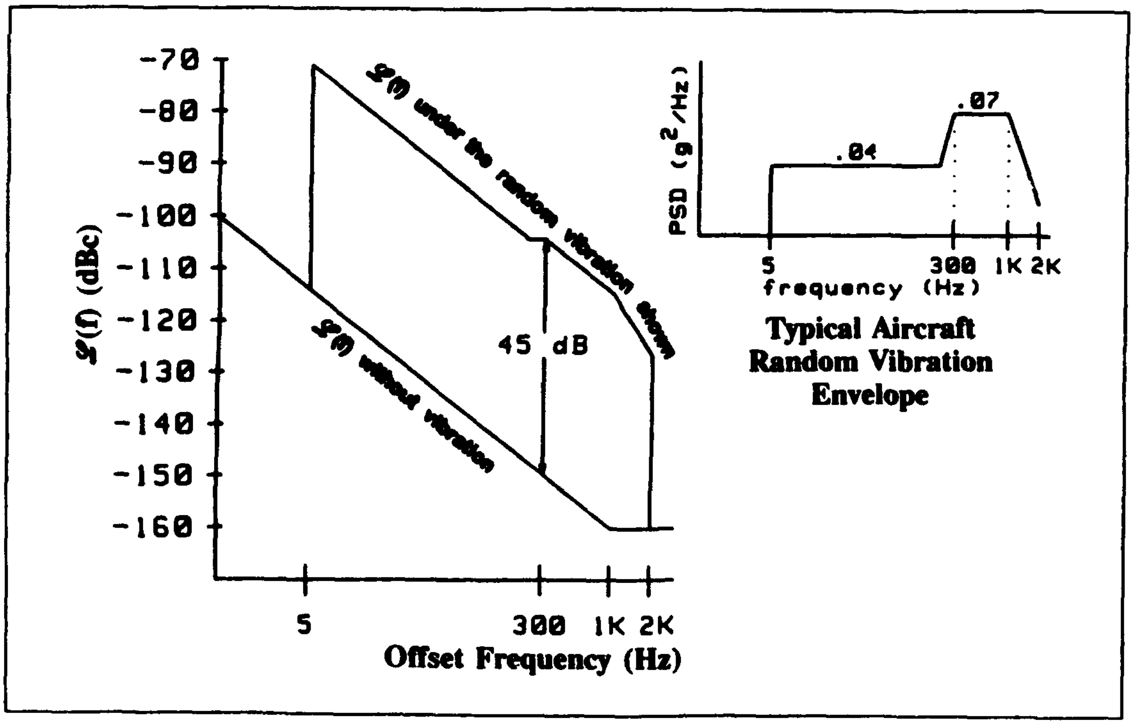


Figure 28. Random-vibration-induced phase-noise degradation.

specification (power spectral density [PSD] vs. vibration frequency) and the resulting vibration-induced phase-noise degradation. Acoustic noise is another source of acceleration that can affect the frequency stability of oscillators.

The peak phase excursion, ϕ_{peak}, due to sinusoidal vibration is

$$\phi_{peak} = \frac{\Delta f}{f_v} = \frac{\vec{\Gamma} \cdot \vec{A} \ f_0}{f_v} \text{ radians.}$$

To some system designers, the quantity of concern is the integrated phase noise in the band f_1 to f_2, which is

$$\Phi^2 = 2\int_{f_1}^{f_2} \mathcal{L}(f)\, df \text{ radians}^2.$$

Upon frequency multiplication, both ϕ_{peak} and Φ increase by the multiplication factor. For example, if $\vec{\Gamma} \cdot \vec{A} = 1 \times 10^{-9}$, $f_0 = 10$ MHz and $f_v = 10$ Hz, then $\phi_{peak} = 1 \times 10^{-3}$ radian. If this oscillator's frequency is multiplied to 10 GHz, e.g., in a radar system, then at 10 GHz, $\phi_{peak} = 1$ radian. Such large phase excursions can be catastrophic to many systems.

Figure 29 shows how the probability of detection for a coherent radar system varies with the phase noise of the reference oscillator [30]. The phase noise requirement for a 90% probability of detection of a 4km/hr target is -130 dBc per Hz at 70 Hz from the carrier, for a 10 MHz oscillator. Such a phase noise is well within the capability of 10 MHz oscillators, provided that the oscillators are in a quiet environment. However, when the oscillators are on a vibrating platform, such as an airborne radar system, the phase noise of even the best available oscillators (as of 1992) is degraded by an amount that reduces the probability of detection to zero.

During shock, a crystal oscillator's frequency changes suddenly due to the sudden acceleration, as is illustrated in Figure 30. The frequency change follows the expression above for acceleration-induced frequency change except, if during the shock some elastic limits in the crystal's support structure or electrodes are exceeded (as is almost always the case during typical shock tests), the shock will produce a permanent frequency change.

Permanent frequency offsets due to shock can also be caused by changes in the oscillator circuitry (e.g., due to movement of a wire or circuit board), and the removal of (particulate) contamination from the resonator surfaces. Resonances in the mounting structure will amplify the shock-induced stress.

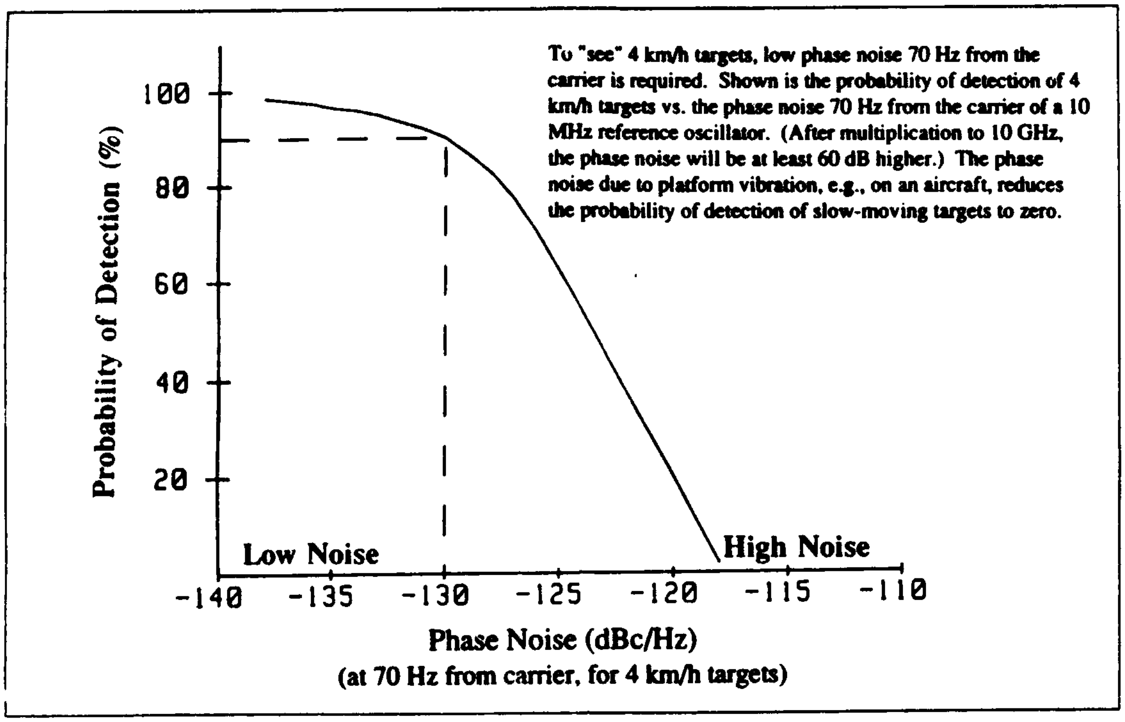


Figure 29. Coherent radar probability of detection as a function of reference oscillator phase noise.

If the shock level is sufficiently high, the crystal will break; however, in applications where high shock levels are a possibility, crystal units with chemically polished crystal plates can be used. Such crystals can survive shocks in excess of 30,000 g and have been fired successfully from howitzers [12,31].

G. Magnetic-Field Effects

Quartz is diamagnetic; however, magnetic fields can affect magnetic materials in the crystal unit's mounting structure, electrodes, and enclosure. Time-varying electric fields will induce eddy currents in the metallic parts. Magnetic fields can also affect components such as inductors in the oscillator circuitry. When a crystal oscillator is designed to minimize the effects of magnetic fields, the sensitivity can be much less than 10^{-10} per oersted. Magnetic-field sensitivities on the order of 10^{-12} per oersted have been measured in crystal units designed specifically for low magnetic-field sensitivity [32].

H. Radiation Effects

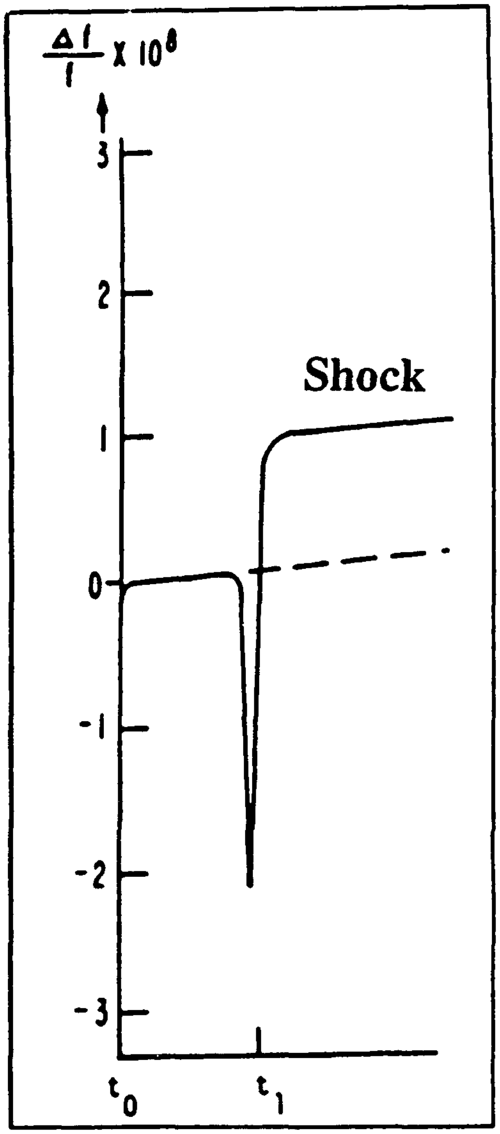


Figure 30. The effect of a shock at $t = t_1$ on oscillator frequency.

Ionizing radiation changes a crystal oscillator's frequency primarily because of changes the radiation produces in the crystal unit [33,34]. Under certain conditions, the radiation will also produce an increase in the crystal unit's equivalent series resistance. The resistance increase can be large enough to stop the oscillation when the oscillator is not radiation hardened.

Figure 31 shows a crystal oscillator's idealized frequency response to a pulse of ionizing radiation. The response consists of two parts. Initially, there is a transient frequency change that is due primarily to the thermal-transient effect caused by the sudden deposition of energy into the crystal unit. This effect is a manifestation of the dynamic *f* vs. *T* effect discussed earlier. The transient effect is absent in SC-cut resonators made of high purity quartz.

In the second part of the response, after steady state is reached, there is a permanent frequency offset that is a function of the radiation dose and the nature of the crystal unit. The frequency change versus dose is nonlinear, the change per rad being much larger at low doses than at large doses. At doses above 1 kilorad (SiO_2), the rate of frequency change with dose is quartz-impurity-defect dependent. For example, at a 1 megarad dose, the frequency change can be as large as 10 ppm when the crystal unit is made from natural quartz; it is typically 1 to a few ppm when the crystal is made from cultured quartz, and it can be as small as 0.02 ppm when the crystal is made from swept cultured quartz.

The impurity defect of major concern in quartz is the substitutional Al^{3+} defect with its associated interstitial charge compensator, which can be an H^+, Li^+, or Na^+ ion, or a hole. This defect substitutes for a Si^{4+} in the quartz lattice. Radiation can result in a change in the position of weakly bound compensators, which changes the elastic constants of quartz and thereby leads to a frequency change. The movement of ions

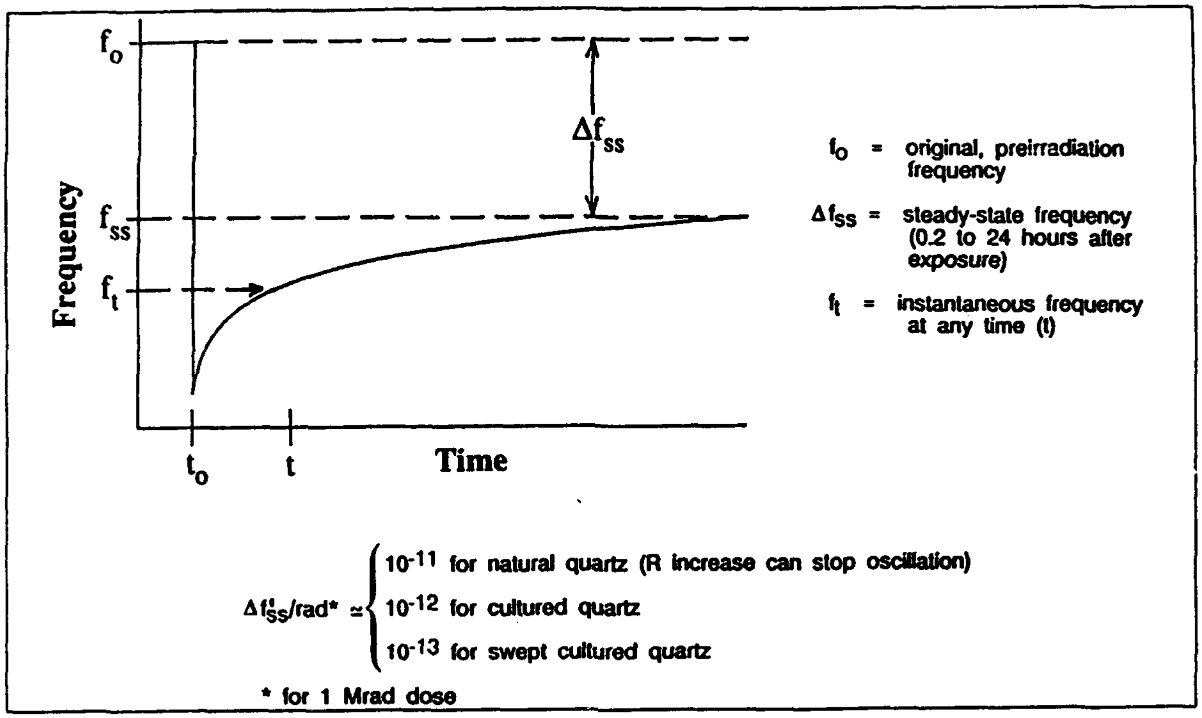


Figure 31. Crystal oscillator's response to a pulse of ionizing radiation: f_o = original preirradiation frequency, Δf_{ss} = steady-state frequency offset (0.2 hours to 24 hours after exposure), f_t = instantaneous frequency at time t.

also results in a decrease in the crystal's Q, i.e., in an increase in the crystal's equivalent series resistance, especially upon exposure to a pulse of ionizing radiation. If the oscillator's gain margin is insufficient, the increased resistance can stop the oscillation for periods lasting many seconds. A high level pulse of ionizing radiation will produce photocurrents in the circuit which result in a momentary cessation of oscillation, independent of the type of quartz used in the resonator. In oscillators using properly designed oscillator circuitry and resonators made of swept quartz, the oscillator recovers within 15 μs after exposure [35,36].

Sweeping is a high-temperature, electric-field-driven, solid-state purification process in which the weakly bound alkali compensators are diffused out of the lattice and replaced by more tightly bound H^+ ions and holes [37,38]. In the typical sweeping process, conductive electrodes are applied to the *Z* surfaces of a quartz bar, the bar is heated to about 500°C, and a voltage is applied so as to produce an electric field of about 1 kilovolt per centimeter along the *Z* direction. After the current through the bar decays (due to the diffusion of impurities) to some constant value, the bar is cooled slowly, the voltage

is removed, and then the electrodes are removed. Crystal units made from swept quartz exhibit neither the radiation-induced Q degradation nor the large radiation-induced frequency shifts. Swept quartz (or low aluminum content quartz) should be used in oscillators which are expected to be exposed to ionizing radiation.

At low doses (e.g., at a few rads) the frequency change per rad can be as high as 10^{-9} per rad [39]. The low-dose effect is not well understood. It is not impurity-dependent, and it saturates at about 300 rads. At very high doses (i.e., at >> 1 Mrad), the impurity-dependent frequency shifts also saturate because, since the number of defects in the crystal are finite, the effects of the radiation interacting with the defects are also finite.

When a fast neutron hurtles into a crystal lattice and collides with an atom, it is scattered like a billiard ball. A single such neutron can produce numerous vacancies, interstitials, and broken interatomic bonds. The effect of this "displacement damage" on oscillator frequency is dependent primarily upon the neutron fluence. The frequency of oscillation increases nearly linearly with neutron fluence at rates of: 8×10^{-21} neutrons per square centimeter (n/cm^2) at a fluence range of 10^{10} to 10^{12} n/cm^2, 5×10^{-21}/n/cm^2 at 10^{12} to 10^{13} n/cm^2, and 0.7×10^{-21}/n/cm^2 at 10^{17} to 10^{18} n/cm^2.

I. Other Effects on Stability

Ambient pressure change (as during an altitude change) can change a crystal oscillator's frequency if the pressure change produces a deformation of the crystal unit's or the oscillator's enclosure (thus changing stray capacitances and stresses). The pressure change can also affect the frequency indirectly through a change in heat-transfer conditions inside the oscillator. Humidity changes can also affect the heat-transfer conditions. In addition, moisture in the atmosphere will condense on surfaces when the temperature falls below the dew point, and can permeate materials such as epoxies and polyimides, and thereby affect the properties (e.g., conductivities and dielectric constants) of the oscillator circuitry. The frequency of a properly designed crystal oscillator changes less than 5×10^{-9} when the environment changes from one atmosphere of air to a vacuum. The medium and long term stability of some oscillators can be improved by controlling the pressure and humidity around the oscillators [40].

Electric fields can change the frequency of a crystal unit. An ideal AT-cut is not affected by a DC voltage on the crystal electrodes, but "doubly rotated cuts," such as the SC-cut, are affected. For example, the frequency of a 5-MHz fundamental mode SC-cut crystal changes 7×10^{-9} per volt. Direct-current voltages on the electrodes can also cause sweeping, which can affect the frequencies of all cuts.

Power-supply and load-impedance changes affect the oscillator circuitry and, indirectly, the crystal's drive level and load reactance. A change in load impedance changes the amplitude or phase of the signal reflected into the oscillator loop, which

changes the phase (and frequency) of the oscillation [41]. The effects can be minimized through voltage regulation and the use of buffer amplifiers. The frequency of a "good" crystal oscillator changes less than 5×10^{-10} for a 10% change in load impedance. The typical sensitivity of a high-quality crystal oscillator to power-supply voltage changes is 5×10^{-11}/V.

Gas permeation under conditions where there is an abnormally high concentration of hydrogen or helium in the atmosphere can lead to anomalous aging rates. For example, hydrogen can permeate into "hermetically" sealed crystal units in metal enclosures, and helium can permeate through the walls of glass-enclosed crystal units.

J. Interactions Among the Influences on Stability

The various influences on frequency stability can interact in ways that lead to erroneous test results if the interfering influence is not recognized during testing. For example, building vibrations can interfere with the measurement of short-term stability. Vibration levels of 10^{-3} g to 10^{-2} g are commonly present in buildings. Therefore, if an oscillator's acceleration sensitivity is 1×10^{-9}/g, then the building vibrations alone can contribute short-term instabilities at the 10^{-12} to 10^{-11} level.

The 2-g tipover test is often used to measure the acceleration sensitivity of crystal oscillators. Thermal effects can interfere with this test because, when an oscillator is turned upside down, the thermal gradients inside the oven can vary due to changes in convection currents [29]. Other examples of interfering influences include temperature and drive-level changes interfering with aging tests; induced voltages due to magnetic fields interfering with vibration-sensitivity tests; and the thermal-transient effect, humidity changes, and the effect of load-reactance temperature coefficient interfering with the measurement of crystal units' static f vs. T characteristics.

An important effect in TCXOs is the interaction between the frequency adjustment during calibration and the f vs. T stability [42]. This phenomenon is called the *trim effect.* In TCXOs, a temperature-dependent signal from a thermistor is used to generate a correction voltage that is applied to a varactor in the crystal network. The resulting reactance variations compensate for the crystal's f vs. T variations. During calibration, the crystal's load reactance is varied to compensate for the TCXO's aging. Since the frequency versus reactance relationship is nonlinear, the capacitance change during calibration moves the operating point on the frequency versus reactance curve to a point where the slope of the curve is different, which changes the compensation (i.e., compensating for aging degrades the f vs. T stability). Figure 32 shows how, for the same compensating C_L vs. T, the compensating f vs. T changes when the operating point is moved to a different C_L. Figure 33 shows test results for a 0.5 ppm TCXO that had a ±6 ppm frequency-adjustment range (to allow for aging compensation for the life of the device). When delivered, this TCXO met its 0.5 ppm f vs. T specification; however, when

the frequency was adjusted ±6 ppm during testing, the f vs. T performance degraded significantly.

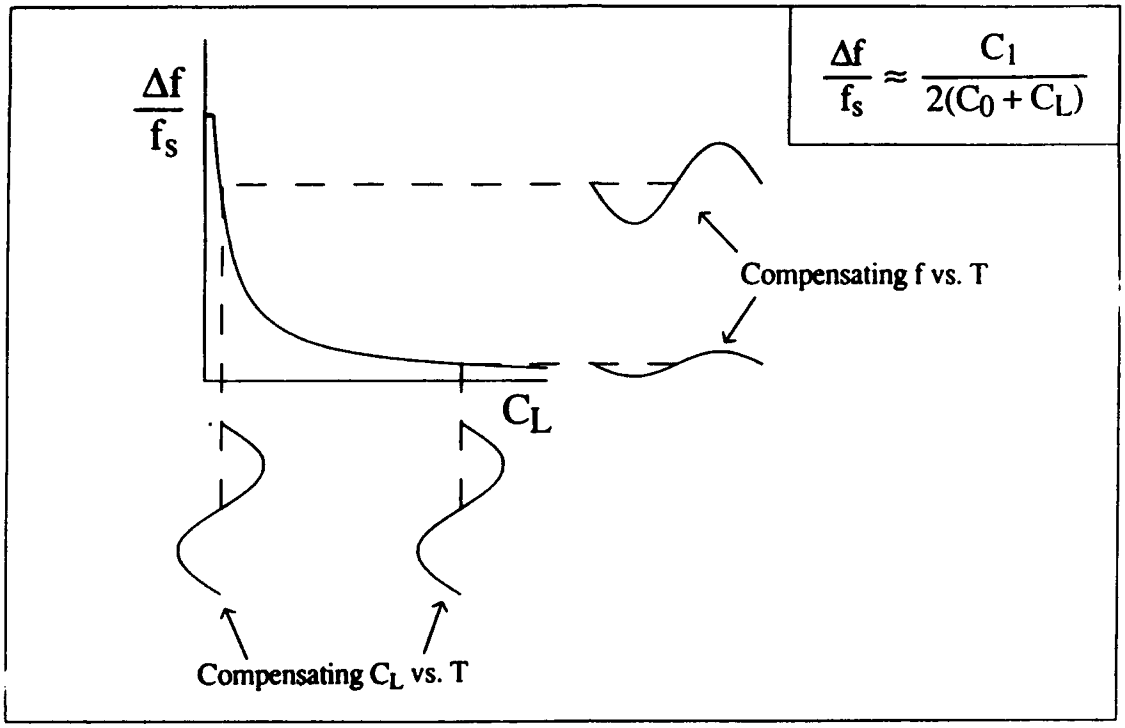


Figure 32. Change in compensating frequency versus temperature due to C_L change.

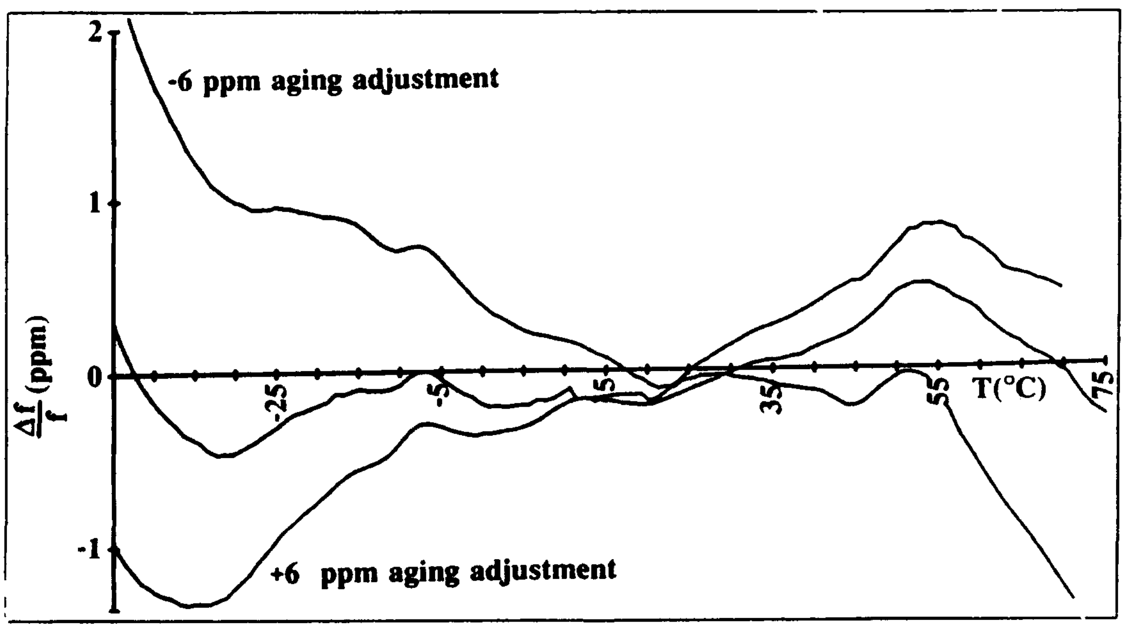
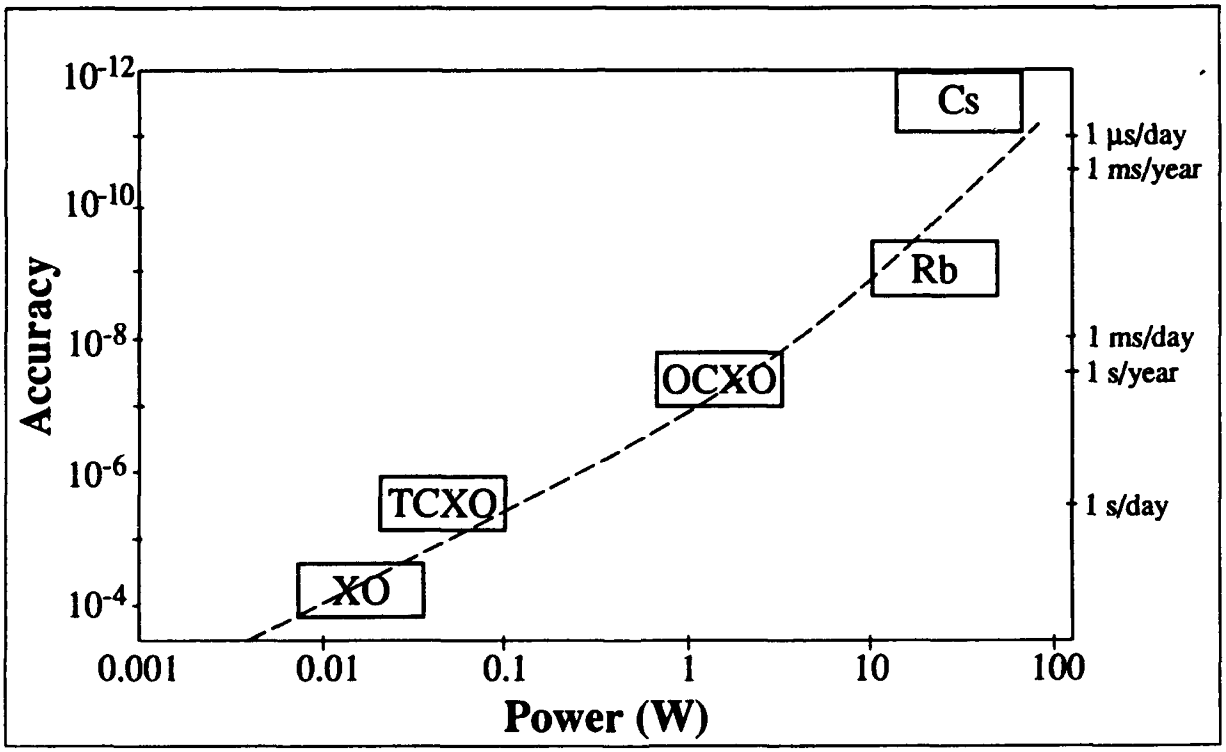


Figure 33. Temperature-compensated crystal oscillator (TCXO) trim effect.

IV. Oscillator Comparison and Selection

The discussion that follows applies to wide-temperature-range frequency standards (i.e., to those which are designed to operate over a temperature range that spans at least 90°C). Laboratory devices that operate over a much narrower temperature range can have better stabilities than those in the comparison below.

Commercially available frequency sources cover an accuracy range of several orders of magnitude--from the simple XO to the cesium-beam frequency standard. As the accuracy increases, so does the power requirement, size, and cost. Figure 34, for example, shows the relationship between accuracy and power requirement. Accuracy versus cost would be a similar relationship, ranging from about $1 for a simple XO to about $40,000 for a cesium standard (1991 prices). Table 1 shows a comparison of salient characteristics of frequency standards. Figure 35 shows the comparison of short term frequency stability ranges as a function of averaging time [43]. Figure 36 shows a comparison of phasa-noise characteristics, and Table 2 shows a comparison of weaknesses and wear-out mechanisms.



* Accuracy vs. size, and accuracy vs. cost have similar relationships.

Figure 34. Relationship between accuracy and power requirements (XO=simple crystal oscillator; TCXO=temperature-compensated crystal oscillator; OCXO=oven-controlled crystal oscillator; Rb=rubidium frequency standard; Cs=cesium beam frequency standard).

Table 1. Comparison of frequency standards' salient characteristics.

	Quartz Oscillators			Atomic Oscillators		
	TCXO	**MCXO**	**OCXO**	**Rubidium**	**RbXO**	**Cesium**
Accuracy * (per year)	2×10^{-6}	6×10^{-8}	1×10^{-8}	5×10^{-10}	7×10^{-10}	2×10^{-11}
Aging/Year	5×10^{-7}	2×10^{-8}	5×10^{-9}	2×10^{-10}	2×10^{-10}	0
Temp. Stab. (range, °C)	5×10^{-7} (-55 to +85)	3×10^{-8} (-55 to +85)	1×10^{-9} (-55 to +85)	3×10^{-10} (-55 to +68)	5×10^{-10} (-55 to +85)	2×10^{-11} (-28 to +65)
Stability, $\sigma_y(\tau)$ ($\tau = 1$ s)	1×10^{-9}	3×10^{-10}	1×10^{-12}	3×10^{-12}	5×10^{-12}	5×10^{-11}
Size (cm^3)	10	50	20-200	800	1200	6000
Warmup Time (min)	0.1 (to 1×10^{-6})	0.1 (to 2×10^{-8})	4 (to 1×10^{-8})	3 (to 5×10^{-10})	3 (to 5×10^{-10})	20 (to 2×10^{-11})
Power (W) (at lowest temp.)	0.05	0.04	0.6	20	0.65	30
Price (~$)	100	1,000	2,000	8,000	10,000	40,000

*Including environmental effects (note that the temperature ranges for Rb and Cs are narrower than for quartz).

Characteristics are provided in Table 1 for atomic oscillators: rubidium and cesium frequency standards and the rubidium-crystal oscillator (RbXO). In atomic frequency standards, the output signal frequency is determined by the energy difference between two atomic states, rather than by some property of a bulk material (as it is in quartz oscillators). An introductory review of atomic frequency standards can be found in reference 44, and reference 45 is a review of the literature up to 1983. (Reference 44 reviews both atomic and quartz frequency standards; the report you are reading is based on the quartz portion of that document.) The RbXO is a device intended for applications where power availability is limited, but where atomic frequency standard accuracy is needed [46,47]. It consists of a rubidium frequency standard, a low-power and high-stability crystal oscillator, and control circuitry that adjusts the crystal oscillator's frequency to that of the rubidium standard. The rubidium standard is turned on periodically (e.g., once a week) for the few minutes it takes for it to warm up and correct the frequency of the crystal oscillator. With the RbXO, one can approach the long-term stability of the rubidium standard with the low (average) power requirement of the crystal oscillator.

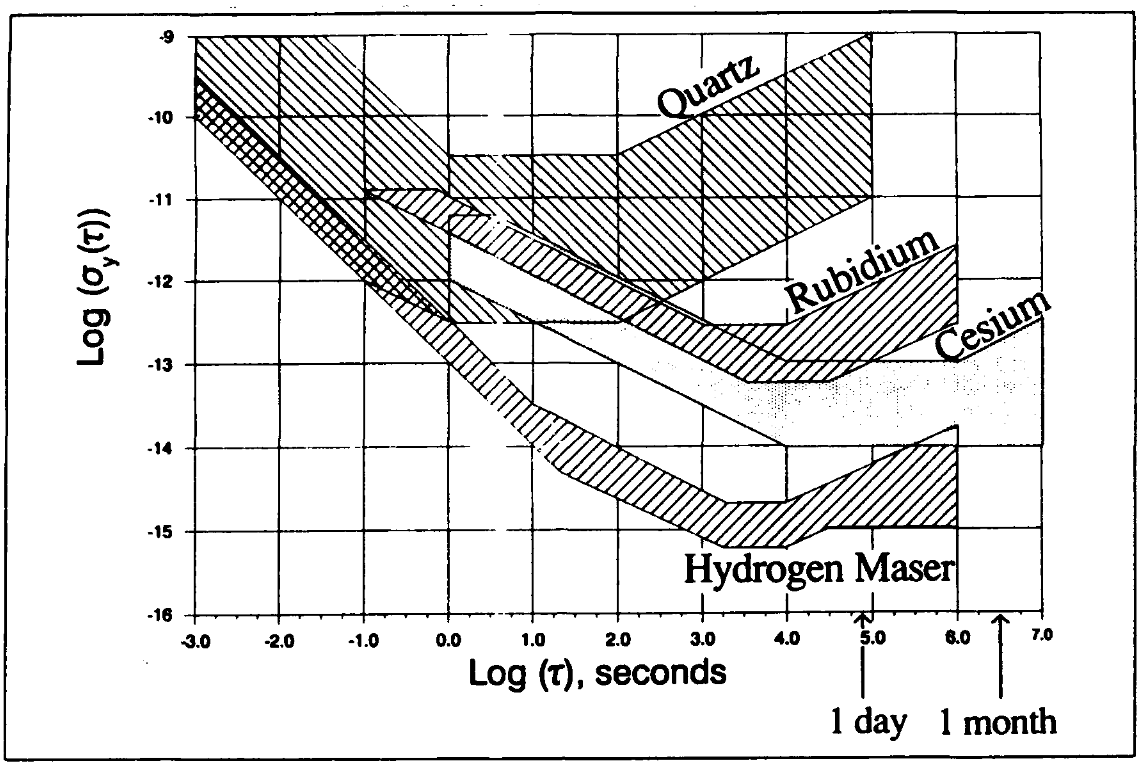
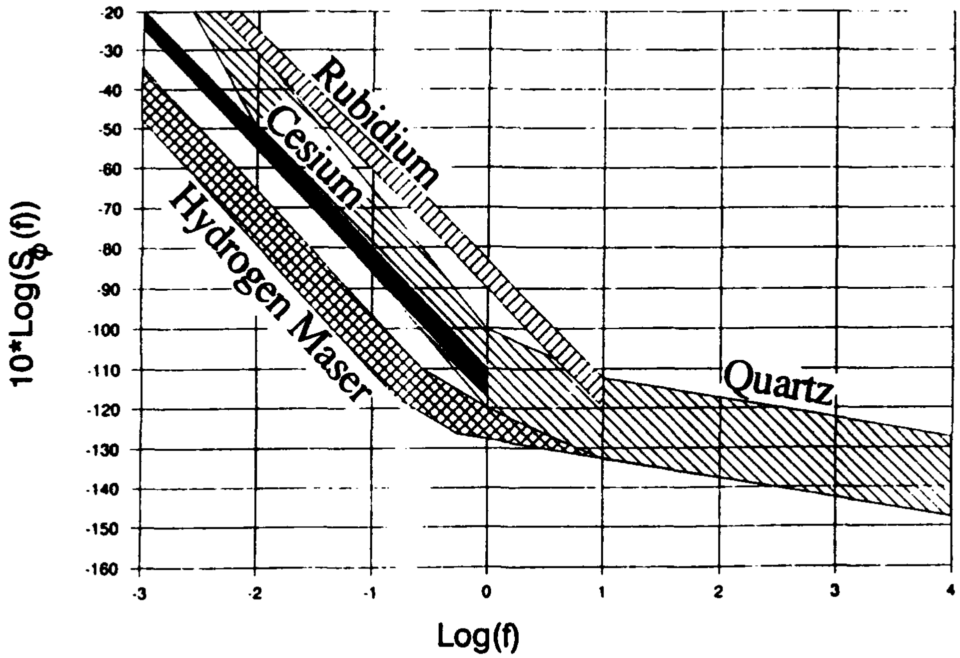


Figure 35. Stability as a function of averaging time comparison of frequency standards.

The major questions to be answered in choosing an oscillator include:

1. What frequency accuracy or reproducibility is needed for the system to operate properly?
2. How long must this accuracy be maintained, i.e., will the oscillator be calibrated or replaced periodically, or must the oscillator maintain the required accuracy for the life of the system?
3. Is ample power available, or must the oscillator operate from batteries?
4. What warmup time, if any, is permissible?
5. What are the environmental extremes in which the oscillator must operate?
6. What is the short-term stability (phase-noise) requirement?
7. What is the size constraint?

In relation to the second question, what cost is to be minimized: the initial acquisition cost or the life-cycle cost? Often, the cost of recalibration is far higher than the added cost of an oscillator that can provide calibration-free life. A better oscillator may also allow simplification of the system's design.



Typical One-sided Spectral Density of Phase Deviation vs. Offset Frequency, for Various Standards, Calculated at 5 MHz.

Figure 36. Phase instability comparison of frequency standards.

Table 2. Comparison of frequency standards' weaknesses and wearout mechanisms.

	Weakness	Wearout Mechanisms
Quartz	Aging Radiation hardness	None
Rubidium	Life Power Weight	Rubidium depletion Buffer gas depletion Glass contaminants
Cesium	Life Power Weight Cost Temperature range	Cesium supply depletion Spent cesium gettering Ion pump capacity Electron multiplier

The frequency of the oscillator is another important consideration, because the choice can have a significant impact on both the cost and the performance. Everything else being equal, an oscillator of standard frequency, such as 5 MHz or 10 MHz, for which manufacturers have well established designs, will cost less than one of an unusual frequency, such as 8.34289 MHz. Moreover, for thickness-shear crystals, such as the AT-cut and SC-cut, the lower the frequency, the lower the aging [17]. Since at frequencies much below 5 MHz, thickness-shear crystals become too large for economical manufacturing, and since all the highest stability oscillators use thickness-shear crystals, the highest stability commercially available oscillator's frequency is 5 MHz. Such oscillators will also have the lowest phase-noise capability close to the carrier. There are also some excellent 10 MHz oscillators on the market; however, oscillators of much higher frequency than 10 MHz have significantly higher aging rates and phase-noise levels close to the carrier than do 5 MHz oscillators. For lowest phase-noise far from the carrier, where the signal-to-noise ratio determines the noise level, higher frequency crystals (e.g., 100 MHz) can provide lower noise because such crystals can tolerate higher drive levels, thereby allowing higher signal levels.

V. Specifications, Standards, Terms, and Definitions

Numerous specifications and standards exist which relate to frequency standards. The major organizations responsible for these documents are the Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), the CCIR, and the U. S. Department of Defense, which maintains the Military Specification (MIL-SPEC) system. A listing of "Specifications and Standards Relating to Frequency Control" can be found in the final pages of the *Proceedings of the IEEE Frequency Control Symposium* (and its predecessor, the *Proceedings of the Annual Symposium on Frequency Control*). In the 1990 *Proceedings*, for example, 79 such documents are listed [48]. Many of the documents include terms and definitions, some of which are inconsistent. Unfortunately, no single authoritative document exists for terms and definitions relating to frequency standards. The terms and definitions in the CCIR glossary [16], in IEEE Std. 1139-1988 [19], and in MIL-O-55310's section 6 [28] are the most recent; they address different aspects of the field, and together form a fairly good set of terms and definitions for users of frequency standards.

The most comprehensive document dealing with the specification of frequency standards is MIL-O-55310 [28]. The evolution of this document over a period of many years has included periodic coordinations between the government agencies that purchase crystal oscillators and the suppliers of those oscillators. The document addresses the specifications of all the oscillator parameters discussed above, plus many others. This specification was written for crystal oscillators. Because the output frequencies of atomic frequency standards originate from crystal oscillators, and because no comparable document exists that addresses atomic standards specifically, MIL-O-55310 can also serve as a useful guide to specifying atomic standards.

MIL-STD-188-115, *Interoperability and Performance Standards for Communications Timing and Synchronization Subsystems*, specifies that the standard frequencies for nodal clocks shall be 1 MHz, 5 MHz, or 5 X 2^N MHz, where N is an integer. This standard also specifies a 1-pulse-per-second timing signal of amplitude 10 V, pulse width of 20 µs, rise time less than 20 ns, fall time less than 1 µs; and a 24-bit binary coded decimal (BCD) time-code that provides Coordinated Universal Time (UTC) time of day in hours, minutes, and seconds, with provisions for an additional 12 bits for day of the year, and an additional four bits for describing the figure of merit (FOM) of the time signal. The FOMs range from BCD Character 1 for better than 1 ns accuracy to BCD character 9 for "greater than 10 ms of fault" [49].

VI. For Further Reading

Reference 4 contains a thorough bibliography on the subject of frequency standards to 1983. The principal forum for reporting progress in the field has been the *Proceedings of the IEEE Frequency Control Symposium* (which was called the *Proceedings of the Annual Symposium on Frequency Control* prior to 1992) [48]. Other publications that deal with frequency standards include *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on Instrumentation and Measurement, Proceedings of the Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting* [50], and *Proceedings of the European Frequency and Time Forum* [51]. Review articles can be found in special issues and publications [52-56].

VII. References

1. Smith, W. L., Precision Oscillators. In: *Precision Frequency Control*, Vol. 2 (E. A. Gerber and A. Ballato, eds.), Academic Press, New York, pp. 45-98, 1985.

2. Frerking, M. E., *Crystal Oscillator Design and Temperature Compensation,* Van Nostrand Reinhold Company, 1978.

3. Bottom, V. E., *Introduction to Quartz Crystal Unit Design,* Van Nostrand Reinhold, New York, 1982.

4. Gerber, E. A. and Ballato, A. (eds.), *Precision Frequency Control,* Academic Press, New York, 1985.

5. Parzen, B., *Design of Crystal and Other Harmonic Oscillators*, Wiley, New York, 1983. Chapter 3 of this book, Piezoelectric Resonators, by A. Ballato, is an oscillator-application oriented treatment of the subject.

6. Hafner, E., Resonator and Device Measurements. In: *Precision Frequency Control,* Vol. 2 (E. A. Gerber and A. Ballato, eds.), Academic Press, pp. 1-44, 1985.

7. Benjaminson, A., Computer-Aided Design of Crystal Oscillators, U. S. Army Laboratory Command R&D Technical Report DELET-TR-84-0386-F, August 1985, AD-B096820; Advanced Crystal Oscillator Design, U. S. Army Laboratory Command R&D Technical Report SLCET-TR-85-0445-F, January 1988, AD-B121288; Advanced Crystal Oscillator Design, U. S. Army Laboratory Command R&D Technical Report SLCET-TR-88-0804-1, February 1989, AD-B134514, and Advanced Crystal Oscillator Design, U. S. Army Laboratory Command R&D Technical Report SLCET-TR-88-0804-F, December, 1991, AD-B163808.

8. Kusters, J. A., Resonator and Device Technology. In: *Precision Frequency Control,* Vol. 1 (E. A. Gerber and A. Ballato, eds.), Academic Press, pp. 161-183, 1985.

9. Meeker, T. R., Theory and Properties of Piezoelectric Resonators and Waves. *In: Precision Frequency Control,* Vol. 1 (E. A. Gerber and A. Ballato, eds.), Academic Press, pp. 47-119, 1985.

10. Kusters, J. A., The SC-cut Crystal - An Overview, *Proc. 1981 Ultrasonics Symp.*, pp. 402-409.

11. R. L. Filler, The Amplitude-Frequency Effect in SC-cut Resonators, *Proc. 39th Ann. Symp. on Frequency Control,* pp. 311-316, NTIS Accession No. AD-A217404, 1985.

12. Vig, J. R., LeBus, J. W., and Filler, R. L., Chemically Polished Quartz, *Proc. 31st Ann. Symp. on Frequency Control,* pp. 131-143, NTIS Accession No. AD-A088221, 1977.

13. Frerking, M. E., Temperature Control and Compensation. In: *Precision Frequency Control,* Vol. 2 (E. A. Gerber and A. Ballato, eds.), Academic Press, New York, pp. 99-111, 1985.

14. Schodowski, S. S., et al., Microcomputer Compensated Crystal Oscillator for Low Power Clocks, *Proc. 21st Ann. Precise Time & Time Interval (PTTI) Applications & Planning Meeting,* pp. 445-464, 1989. Available from the U. S. Naval Observatory, Time Services Department, 34th and Massachusetts Avenue, NW, Washington, DC 20392. Details of the MCXO are also described in a series of five papers in the *Proc. 43rd Ann. Symp. Frequency Control,* NTIS Accession No. AD-A235629, 1989.

15. XIIIth General Conference of Weights and Measures, Geneva, Switzerland, October 1967.

16. International Radio Consultative Committee (CCIR), Recommendation No. 686, Glossary. In: *CCIR 17th Plenary Assembly,* Vol. 7, Standard Frequencies and Time Signals (Study Group 7), CCIR, Geneva, Switzerland, 1990. Copies available from

International Telecommunications Union, General Secretariat - Sales Section, Place des Nations, CH1211 Geneva, Switzerland.

17. Vig, J. R., and Meeker, T. R., The Aging of Bulk Acoustic Wave Resonators, Filters, and Oscillators, *Proc. 45th Ann. Symp. Frequency Control*, IEEE Cat. No. 91CH2965-2, pp. 77-101, 1991.

18. Rutman, J., and Walls, F. L., Characterization of Frequency Stability in Precision Frequency Sources, *Proc. of the IEEE,* Vol. 79, No. 6, pp. 952-960, June 1991.

19. IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology, *IEEE Std. 1139-1988.* IEEE, 445 Hoes Lane, Piscataway, NJ 08854, U.S.A.

20. Parker, T. E., Characteristics and Sources of Phase Noise in Stable Oscillators, *Proc. 41st Ann. Symp. on Frequency Control*, pp. 99-110, NTIS Accession No. AD-A216858, 1987.

21. Ballato, A. and Lukaszek, T., Higher Order Temperature Coefficients of Frequency of Mass-Loaded Piezoelectric Crystal Plates, *Proc. 29th Ann. Symp. on Frequency Control,* pp. 10-25, NTIS Accession No. AD-A017466, 1975.

22. Ballato, A. and Vig, J. R., Static and Dynamic Frequency-Temperature Behavior of Singly and Doubly Rotated, Oven-Controlled Quartz Resonators, *Proc. 32nd Ann. Symp. on Frequency Control*, pp. 180-188, NTIS Accession No. AD-A955718, 1978.

23. Ballato, A. and Tilton, R., Electronic Activity Dip Measurement, *IEEE Trans. on Instrumentation and Measurement*, Vol. IM-27, pp. 59-65, 1978.

24. Ballato, A., Frequency-Temperature-Load Capacitance Behavior of Resonators for TCXO Applications, *IEEE Trans.Sonics and Ultrasonics*, SU-25, pp. 185-191, July 1978.

25. Filler, R. L., Frequency-Temperature Considerations for Digital Temperature Compensation, *Proc. 45th Ann. Symp. on Frequency Control*, pp. 398-404, IEEE Cat. No. 87CH2965-2, 1991.

26. Filler, R. L., Measurement and Analysis of Thermal Hysteresis in Resonators and TCXOs, *Proc. 42nd Ann. Symp. Frequency Control*, pp. 380-388, NTIS Accession No. AD-A217275, 1988.

27. Kusters, J. A., and Vig, J. R., Thermal Hysteresis in Quartz Resonators - A Review, *Proc. 44th Ann. Symp. Frequency Control,* pp. 165-175, IEEE Catalog No. 90CH2818-3, 1990.

28. U.S. Department of Defense, Military Specification, Oscillators, Crystal, General

28. U.S. Department of Defense, Military Specification, Oscillators, Crystal, General Specification for, MIL-O-55310. The latest revision is available from Military Specifications and Standards, 700 Robbins Ave., Bldg. 4D, Philadelphia, PA 19111-5094.

29. Vig, J. R., et al., Acceleration, Vibration and Shock Effects - IEEE Standards Project P1193, *Proc. 1992 IEEE Frequency Control Symposium*, IEEE Cat. No. 92CH3083-3, 1992; also, Vig, J. R., et al., *The Effects of Acceleration on Precision Frequency Sources (Proposed for IEEE Standards Project P1193)*, U.S. Army Laboratory Command Research and Development Technical Report SLCET-TR-91-3, March 1991. Copies available from National Technical Information Service, 5285 Port Royal Road, Sills Building, Springfield, VA 22161; NTIS Accession No. AD-A235470.

30. Taylor, J., Effects of Crystal Reference Oscillator Phase Noise in a Vibratory Environment, Technical Memorandum 2799-1011, Motorola, SOTAS Engineering Development Section, Radar Operations, August 8, 1980. The Stand-Off Target Acquisition System (SOTAS) was a helicopter-borne coherent radar system that was being developed for the U.S. Army; the program was canceled before completion. To meet the 90% probability of detection goal for 4 km/h targets while operating from a helicopter, the system required a reference oscillator acceleration sensitivity of 4×10^{-12} per g, which was about 100-fold beyond the state-of-the-art at the time.

31. Filler, R. L., et al., Ceramic Flatpack Enclosed AT and SC-cut Resonators, *Proc. 1980 IEEE Ultrasonic Symp.*, pp. 819-824, 1980.

32. Brendel, R., et al., Influence of Magnetic Field on Quartz Crystal Oscillators, *Proc. 43rd Ann. Symp. Frequency Control*, pp. 268-274, NTIS Accession No. AD-A235629, 1989.

33. King, J. C., and Koehler, D. R., Radiation Effects on Resonators. In: *Precision Frequency Control*, Vol. 2 (E. A. Gerber and A. Ballato, eds.), Academic Press, New York, pp. 147-159, 1985.

34. Suter, J. J., et al., The Effects of Ionizing and Particle Radiation on Precision Frequency Sources, *Proc. 1992 IEEE Frequency Control Symposium*, IEEE Cat. No. 92CH3083-3, 1992.

35. King, J. C. and Sander, H. H., Rapid Annealing of Frequency Change in High Frequency Crystal Resonators Following Pulsed X-irradiation at Room Temperature, *Proc. 27th Ann. Symp. Frequency Control*, pp. 117-119, NTIS Accession No. AD-771042, 1973.

36. Paradysz, R. E. and Smith W. L., Crystal Controlled Oscillators for Radiation Environments, *Proc. 27th Ann. Symp. Frequency Control*, pp. 120-123, NTIS Accession No. AD-771042, 1973.

37. Martin, J. J., Electrodiffusion (Sweeping) of Ions in Quartz, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 35, No. 3, pp. 228-296, May IEEE Catalog 88CH2588-2, 1988.

38. Gualtieri, J. G., Sweeping Quartz Crystals, *Proc. 1989 IEEE Ultrasonics Symp.*, pp. 381-391, 1989.

39. Flanagan, T. M., Leadon, R. E., and Shannon, D. L., Evaluation of Mechanisms for Low-Dose Frequency Shifts in Crystal Oscillators, *Proc. 40th Ann. Symp. Frequency Control*, pp. 127-133, NTIS Accession No. AD-A235435, 1986.

40. Walls, F. L., The Influence of Pressure and Humidity on the Medium and Long-Term Frequency Stability of Quartz Oscillators, *Proc. 42nd Ann. Symp. on Frequency Control*, pp. 279-283, NTIS Accession No. AD-A217725, 1988.

41. Walls, F. L., Environmental Sensitivities of Quartz Crystal Oscillators, *Proc. 22nd Ann. Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, pp. 465-477, NTIS Accession No. AD-A239372, 1990.

42. Filler, et al., Specification and Measurement of the Frequency Versus Temperature Characteristics of Crystal Oscillators, *Proc. 43rd Ann. Symp. Frequency Control*, pp. 253-256, NTIS Accession No. AD-A235629, 1989.

43. The graphs in Figures 34 and 35 were prepared in 1989 for a CCIR document by Richard Sydnor, Jet Propulsion Laboratories.

44. Stein, S. R. and Vig, J. R., Communications Frequency Standards, in: *The Froelich/Kent Encyclopedia of Telecommunications*, Vol. 3 (Froehlich, F. E. and Kent, A. eds.), Marcel Dekker, Inc., New York, 1992, pp. 445-500. A reprint of this chapter is available under the title "Frequency Standards for Communications," as U. S. Army Laboratory Command Technical Report SLCET-TR-91-2 (Rev. 1), October 1991, NTIS Accession No. AD-A243211.

45. Hellwig, H., Microwave Time and Frequency Standards, In: *Precision Frequency Control*, Vol. 2 (E. A. Gerber and A. Ballato, eds.), Academic Press, New York, 1985, pp. 113-176.

46. Vig, J. R. and V. J. Rosati, The Rubidium-Crystal Oscillator Hybrid Development Program, *Proceedings of the 16th Annual PTTI Applications and Planning Meeting*, 1984, pp. 157-165.

47. Riley, W. J. and Vaccaro, J. R., A Rubidium-Crystal Oscillator (RbXO), *IEEE Trans. on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. UFFC-34, pp. 612-618, 1987.

48. The Proceedings of the IEEE Frequency Control Symposium, and its predecessor, the Proceedings of the Annual Symposium on Frequency Control, have been published since the tenth symposium in 1956. The latest volumes are available from the IEEE, 445 Hoes Lane, Piscataway, NJ 08854. The earlier volumes are available from the National Technical Information Service, 5285 Port Royal Road, Sills Building, Springfield, VA 22161, USA. Ordering information for all the *Proceedings* can be found in the back of the latest volumes (e.g., the *Proceedings of the 45th Annual Symposium on Frequency Control* 1991 is available from the IEEE, Cat. No. 91CH2965-2, and the *Proceedings of the 1992 IEEE Frequency Control Symposium* is Cat. No. 92CH3083-3).

49. U.S. Department of Defense, Military Standard, MIL-STD-188-115, *Interoperability and Performance Standards for Communications Timing and Synchronization Subsystems.* The latest revision is available from Military Specifications and Standards, 700 Robbins Avenue, Building 4D, Philadelphia, PA 19111-5094.

50. *The Proceedings of the Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting* are available from the U. S. Naval Observatory, Time Services Department, 34th and Massachusetts Ave., N.W., Washington, DC 20392-5100. The latest volumes are also available from the National Technical Information Service, 5285 Port Royal Road, Sills Building, Springfield, VA 22161, USA.

51. The *Proceedings of the European Frequency and Time Forum* are available from the Swiss Foundation for Research in Metrology (FSRM), Rue de l'Orangerie 8, CH-2000 Neuchatel, Switzerland.

52. *IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control,* UFFC-34, November 1987.

53. *IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control,* UFFC-35, May 1988.

54. Kroupa, V. F. (ed.), *Frequency Stability: Fundamentals and Measurement,* IEEE Press, New York, 1983.

55. Sullivan, D. B., et al. (eds.), *Characterization of Clocks and Oscillators,* National Institute of Standards and Technology Technical Note 1337, National Institute of Standards and Technology, Boulder, CO 80303-3328.

56. *Proceedings of the IEEE,* Special Issue on Time and Frequency, Vol. 79, No. 7, July 1991.